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ARMSTRONG LABORATORY

ACOUSTIC EMISSION METHODS FOR THE DETECTION OF LEAKS IN UNDERGROUND STORAGE TANKS AND PIPELINES

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13. ABSTRACT *(Maximum 200 words)*
The objective of this Small Business Innovative Research (SBIR) Phase I study was to investigate the feasibility of applying advanced acoustic emission (AE) instrumentation and methodology to the detection of small leaks in large underground fuel storage tanks (USTs) and associated pipelines. This technology has been successfully used to test for leaks in the floors of large above-ground petrochemical storage tanks. Laboratory testing was conducted by mounting two acoustic sensors to a leak test apparatus. As the leak hole size, hydrostatic pressure head, and surrounding soil types were varied, the acoustic signal levels within 16 frequency bands were monitored. A leak source emits a characteristic acoustic signature that travels through both the storage vessel walls and liquid until it arrives at the monitoring sensors. Software routines were developed to distinguish this signal from random unrelated background noise using two distinct leak detection approaches, activity-detection and location-detection. Experimental results showed a minimum detection leak rate of approximately 0.4 gal/hr. Continued laboratory development to improve the detection sensitivity was recommended. This would be followed by field test evaluation.

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Acoustic Emission, Acoustics, Leak, Leak Detection, Storage Tank, Pipeline

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PREFACE

This technical report was originally prepared by Pelagos Corporation, 9173 Chesapeake Drive, San Diego, California 92123, under Contract Number FO 8635-87-C-0365 for the Air Force Engineering and Services Center. The work was accomplished as a SBIR Phase I effort, but the technical report was never published.

This report summarizes work accomplished between 3 August 1987 and 30 April 1988. Mr. Hari B. Bindal was then the project manager.

Although the research is over 4 years old and the distribution limitation for SBIR has expired, the report is being published by this Directorate because of its interest to the DOD scientific and engineering community.

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SUMMARY

The objective of this study was to develop and apply advanced acoustic emission (AE) monitoring methods for the detection of leaks in U.S. Air Force underground fuel storage tanks (USTs) and associated piping. The Air Force currently relies upon chemical tracing and groundwater sampling methods of leak detection. AE technology can provide faster, safer and more sensitive determination. AE testing methods were originally developed by the nuclear industry for the detection and location of crack flaws in reactor vessels and cooling system components. Additional leak monitoring applications include petrochemical valves, vessels, heat exchangers, pipelines, and above-ground storage tanks. Pelagos Corporation is presently using advanced AE monitoring systems and methods to test for leaks in the floors of large above-ground petrochemical storage tanks. This SBIR Phase I feasibility evaluation represents the application of existing capabilities and laboratory development of new hardware, software and test procedures.

The primary leak test apparatus consisted of a 20-foot length of 1.5-inch-diameter steel pipe placed horizontally a few inches above the floor. Test leak holes (0.014- and 0.021-inch-diameter) were drilled in a 6-inch-long section of the pipe. This section was then buried in a soil box. A water supply reservoir was positioned above the pipe to provide an adjustable hydrostatic pressure head. Acoustic sensors were attached to the pipe near each end. In some tests, an accelerometer replaced one of the AE sensors. The test format consisted of a selected leak size, pressure head (up to 15 feet) and soil type (sandy, silty, clayey). Acoustic emission data were recorded for 16 frequency bands between 18 and 288 kHz. The data processing software routines supported two approaches to leak detection: activity-detection; and location-detection. In the activity-detection operational mode, data set average, standard deviation and peak statistics were calculated. As expected, the activity level, as measured by the S/N distribution statistics, increased with increasing pressure head. The 18 and 36 kHz AE sensor frequency bands were observed to be particularly sensitive. Leak rates of 0.4 gallons per hour and greater were reliably detected for

pressure heads of 12 to 15 feet. The three soil types showed comparable results. In the location-detection mode, the differential arrival times are used to solve for the location of the leak. Leak rates of 0.4 gallons per hour were reliably detected and located for pressure heads of 11 to 12 feet. Both leak detection methods have a verification feature. By decreasing the pressure head in the tanks to a lower level, all real leak signals can be eliminated.

Based on these positive results, it is expected that the detection sensitivity can be considerably improved to 0.1 gallons per hour by further testing and development. Additional laboratory research and applied in-field system evaluations are recommended.

TABLE OF CONTENTS

LIST OF FIGURES

(LIST OF FIGURES)
(CONTINUED)

(LIST OF FIGURES)
(CONCLUDED)

LIST OF ABBREVIATIONS

AE	Acoustic Emission
AELL	Acoustic Emission Leak Locator
ASTM	American Society For Testing and Materials
A/D	Analog-to-Digital
Avg	Average
dB	Decibel
Freq	Frequency
gal/hr	Gallons per hour
kHz	Kilohertz
LCD	Liquid Crystal Display
ms	Milliseconds
Peak Amp	Peak Amplitude
psi	Pounds per Square Inch
Std Dev	Standard Deviation
S/N	Signal-to-Noise
UST	Underground Storage Tank

SECTION I

INTRODUCTION

A. OBJECTIVES

The overall objective of this effort is to develop and apply advanced acoustic-emission (AE) monitoring methods for the detection of leaks in U.S. Air Force (U.S.A.F.) underground fuel storage tanks (USTs), and associated piping. Any detection method developed should use only sensors which may be mounted externally to the tank/pipe containments.

B. BACKGROUND

The U.S.A.F. requires methods of detecting leaks in their large underground aircraft refueling tanks which are located at various Air Force bases. Any methods developed should be faster, safer and more sensitive than the current methods which rely upon chemical tracing and groundwater sampling.

Pelagos Corporation currently uses advanced AE monitoring systems and methods to test for leaks in the floors of large above-ground petrochemical storage tanks which usually contain volatile hydrocarbon products. Much of this experience can be applied to the monitoring of USTs. However, problems arise due to: 1) the limited access for attachment of sensors on underground tanks compared to the easy access to the sidewalls of above-ground tanks; and 2) the U.S.A.F. requirement for the most sensitive detection capability. Therefore, new hardware, software, and test methods must be developed for this application.

Acoustic Emission (AE) technology was developed primarily by the nuclear industry, for detection and location of crack flaws in reactor vessels and associated coolant system piping. During the 1970's, the nuclear AE test programs (references 1-4) also extended the technology for use in monitoring high pressure (500-2000 psi) leaks occurring in nuclear systems.

More recent applications include monitoring for leaks in petrochemical valves, vessels, heat exchangers, pipelines and above-ground storage tanks. The monitoring of leaks in the floors of above-ground storage tanks (references 6-7) is the most similar application to underground storage tanks since both situations involve a low-pressure static product head as the leak driving force. However, there is currently no requirement for a very high sensitivity, e.g. 0.1 gallons per hour leak rate for above-ground storage tanks. A capability to acoustically detect leaks of one-sixteenth inch diameter is a big improvement over the method of leak detection by still-gauging (no input or output) of a decrease in the tank product level. Reference 7 reports, "Acoustic Emission has located leaks with diameters from 1mm (0.04 inches), maximum differential pressure of 50 kilopascal (equivalent to approximately 7.25 psi or 16.7 feet of water) and one evaluation of the AE method's lowest detectable leakage was 1.7 liters/hour (equivalent to approximately 0.45 gal/hr) at the experimental tank".

The U.S.A.F. funded an AE leak detection program during 1980-1986, for detection of leaks in satellite fuel systems. The Marquardt Company was the prime contractor; Acoustic Emission Leak Locations Corporation (AELL) was the primary subcontractor. The principal investigator of this proposed Phase I effort was closely involved in this program while employed at AELL. The reported results (Reference 8) show that it is possible to detect leaks of less than 0.05 gallons per hour using specially designed sensors and signal processing electronics. This testing was performed at pressures of 50 psi (equivalent to approximately 115 feet of water) and greater. A JANNAF paper on this program reports "The program demonstrated that an automatic satellite leak detection and isolation system was feasible and that liquid leaks as low as 45 gm/hr (equivalent to approximately 0.01 gal/hr) could be detected.

C. SCOPE/APPROACH

The following guidelines were established by Pelagos and the U.S.A.F. program officer during the initial program effort:

1. The primary fuel in the USTs is jet fuel JP-4. Comparative tests of the acoustic leak characteristics of JP-4 and water will be made early in the program. If water exhibits similar acoustic characteristics, as expected, then water will be used as the test fluid throughout the effort.

2. The initial technical goal is to achieve a sensitivity for detection of leaks of 0.1 gallon per hour (gal/hr), using available AE leak detection equipment. If this is not possible, then a minimum detectable leak rate will be determined.

3. The detection method must be able to operate in the presence of aircraft, ground vehicle, and other airfield noises.

4. Tank leaks will be more difficult to detect than pipeline leaks, since the tanks cannot be pressurized by an external source. The tank pressure can be increased only by the addition of more inventory (head) in the tank. Associated piping can be proof-tested separately from the tank, and at a higher pressure level, e.g. 50 psi is used for the piping of gas station tanks. The detection of a pipe leak at 50 psi is much easier to identify than a tank leak at about 7 psi. For this reason, the testing will emphasize detection of low-pressure tank-type leaks having 1 to 15 feet of head.

5. Any monitoring sensors will be attached directly to the tank structure or piping using the methods developed in this program. The lower leak signal caused by the low pressure (leak) head, and the higher noise background caused by aircraft presence make it impractical to use sensors which listen for leaks through the ground.

6. The primary test parameters will be leak rate, pressure head and soil type. There are many combinations of leak size, leak configuration, pressure head and soil type which can exist in field test situations. Since our experience has shown that small differences in leak circumstances can significantly affect the acoustic signal characteristics, the testing will not involve precise and repeated measurements for given situations.

7. The majority of the effort will involve the development of methods and associated hardware and software. The resulting hardware/software system developed will be evaluated for detection sensitivity in selected leak situations. For simplicity, leak holes will be drilled and sections of pipe will be used to simulate a tank environment.

SECTION II

MONITORING SYSTEM DESIGN

A. HARDWARE

Figure 1 shows the hardware configuration developed during this effort.

Development consisted chiefly of interfacing the portable Acoustic Emission Leak Locator (AELL-2000) two-channel monitoring system with the IBM AT-compatible computer system using of an analog-to-digital computer module. The AELL-2000 filter-amplifier-rectifier instruments do not have any capability for output of data or for remote control of the monitor frequency. It does have 16 frequency bands controlled by a front-panel switch and an LCD digital display. The AELL-2000 filter bands were modified to be highly responsive to small transient signals.

The interfacing provided output signals from each of the two channels which were input to two channels of the A/D converter. It also provided output from the computer in order to digitally control, by software command, the monitor frequency band of the two channels.

During operation, the software simultaneously switches the frequencies of both channels. The range of the 16 frequency bands can be changed by substituting different filter cards. When two standard Pelagos AE sensors are being used, the filters cover an 18-to 288-kilohertz (kHz) range. When an accelerometer is used with channel 2, its filter is set up to cover a 2.5-to 40-kHz range.

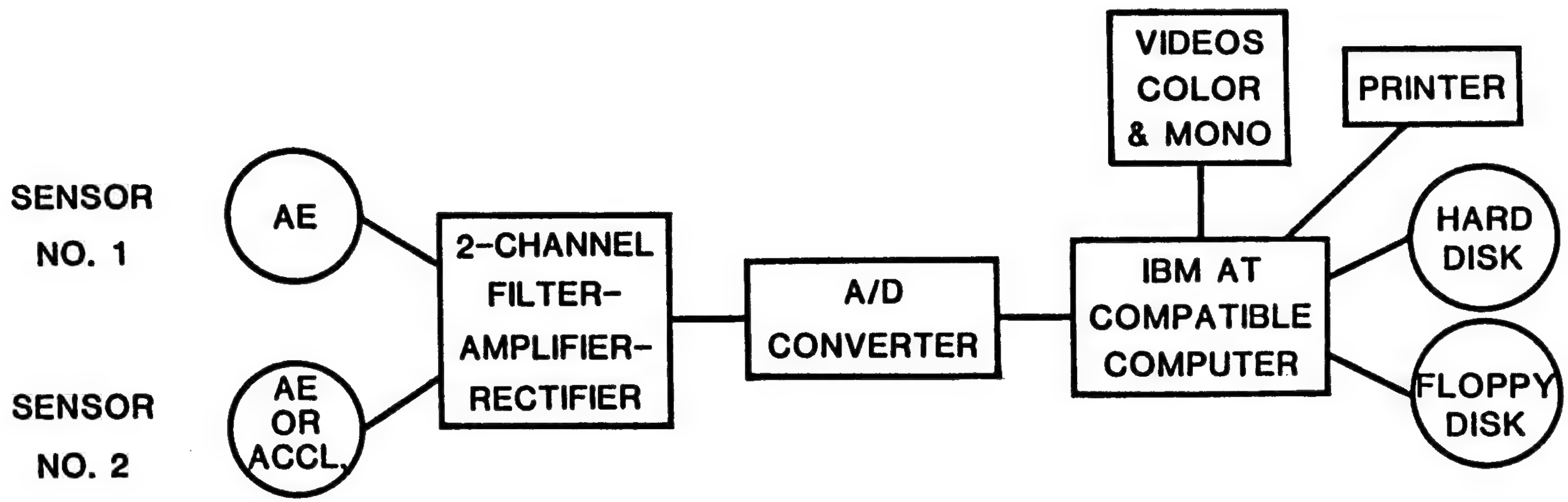


Figure 1. AE Monitoring System Configuration

B. SOFTWARE

Two approaches to leak detection were considered: "activity detection"; and "location detection". Four software routines were written in order to pursue these approaches.

The first software package, FSCAN, measures the acoustic activity (for each of the 16 frequency bands) of the container as monitored by two sensors. The program sequentially steps through the frequencies, taking a 0.5-second-duration data set for each frequency and channel. It converts each channel at a 3-kHz sample rate, and records the data on both floppy and hard disks.

The second software package, STATS, retrieves the FSCAN file data and calculates data-set averages, standard deviations, and peak values. It displays and prints the output in tabular form. Table 1 is an example presentation of actual leak data.

With this output, an operator can easily compare activity under different test-leak situations. He is able to "stimulate" the container by changing the liquid level and then immediately recognize the corresponding signal response. This stimulation is done by adding or removing pressure head to the tank. A standpipe is attached to the tank inlet or outlet pipes. By adding a few gallons of liquid to the standpipe, the pressure head can be increased from, say, 10 to 15 feet. This procedure is not difficult or unsafe. In fact, the majority of leak detection done for underground tanks in gasoline stations involves similar use of a standpipe. (During this procedure, the test technician watches for a level drop in the standpipe due to leakage loss.)

Table 1

Example of Statistical Data Output
Generated By FSCAN and STATS Programs

	CH 1				CH 2			
Freq Band	Avg	Std Dev	Peak Amp	Peak Time	Avg	Std Dev	Peak Amp	Peak Time
1	0.205	0.124	0.967	471	0.097	0.038	0.247	665
2	0.187	0.104	0.818	1384	0.089	0.026	0.212	1265
3	0.265	0.146	1.331	8	0.136	0.035	0.293	1109
4	0.228	0.104	0.967	338	0.173	0.041	0.332	398
5	0.295	0.163	2.620	211	0.212	0.048	0.437	1280
6	0.408	0.186	1.619	193	0.280	0.110	0.796	1089
7	0.470	0.265	3.970	571	0.294	0.079	0.532	804
8	0.398	0.217	2.261	957	0.305	0.079	0.649	992
9	0.301	0.174	1.377	1130	0.315	0.111	1.045	565
10	0.192	0.099	0.811	1216	0.360	0.086	0.706	1439
11	0.108	0.051	0.381	1142	0.317	0.077	0.679	1143
12	0.084	0.040	0.420	713	0.307	0.065	0.547	592
13	0.060	0.029	0.225	1477	0.654	0.381	2.021	1045
14	0.046	0.024	0.195	504	0.303	0.193	1.787	63
15	0.035	0.020	0.173	173	0.250	0.060	0.525	1006
16	0.022	0.014	0.112	631	0.212	0.062	0.461	269

The activity-detection method described above is similar to the procedures widely used for AE monitoring of cracks in vessels and pipes. In this application, the internal pressure is increased thereby causing increased stress on any flaws. The flaws emit stresswaves, i.e. increase their acoustic activity. This method has been used for about ten years and conforms to American Society For Testing and Materials (ASTM) procedures (Reference E650-78 and E750-80).

The second method of leak detection developed and applied in this effort, "location detection", involves determining the location of acoustic "events" emitted by a leak. An event, e.g. a "sputtering" transient noise, emitted at the leak source, travels through both the tank liquid and the wall until it arrives first at the closest sensor and later at the most remote sensor. The monitoring system measures the arrival times at each sensor for many such events (transients), and accumulates the results as differences between the arrival times. If one arrival-time-difference is much more dominant than the others, then there is an active acoustic source in the tank. This source is very likely a leak.

Software routines called LOCATE and PEAKSORT were developed to perform this location function. The results of this program are displayed and printed in Figure 2. In this figure, the data show how a leak location is determined. The abscissa represents arrival-time-differences in milliseconds (ms) relative to the midpoints of the sensor separation, i.e. the test-pipe midpoint. Any leak events emitted at the midpoint would arrive at the sensors simultaneously, giving a time difference of zero milliseconds. The height of the vertical lines represents the cumulative number of events located in each "delta-time" interval.

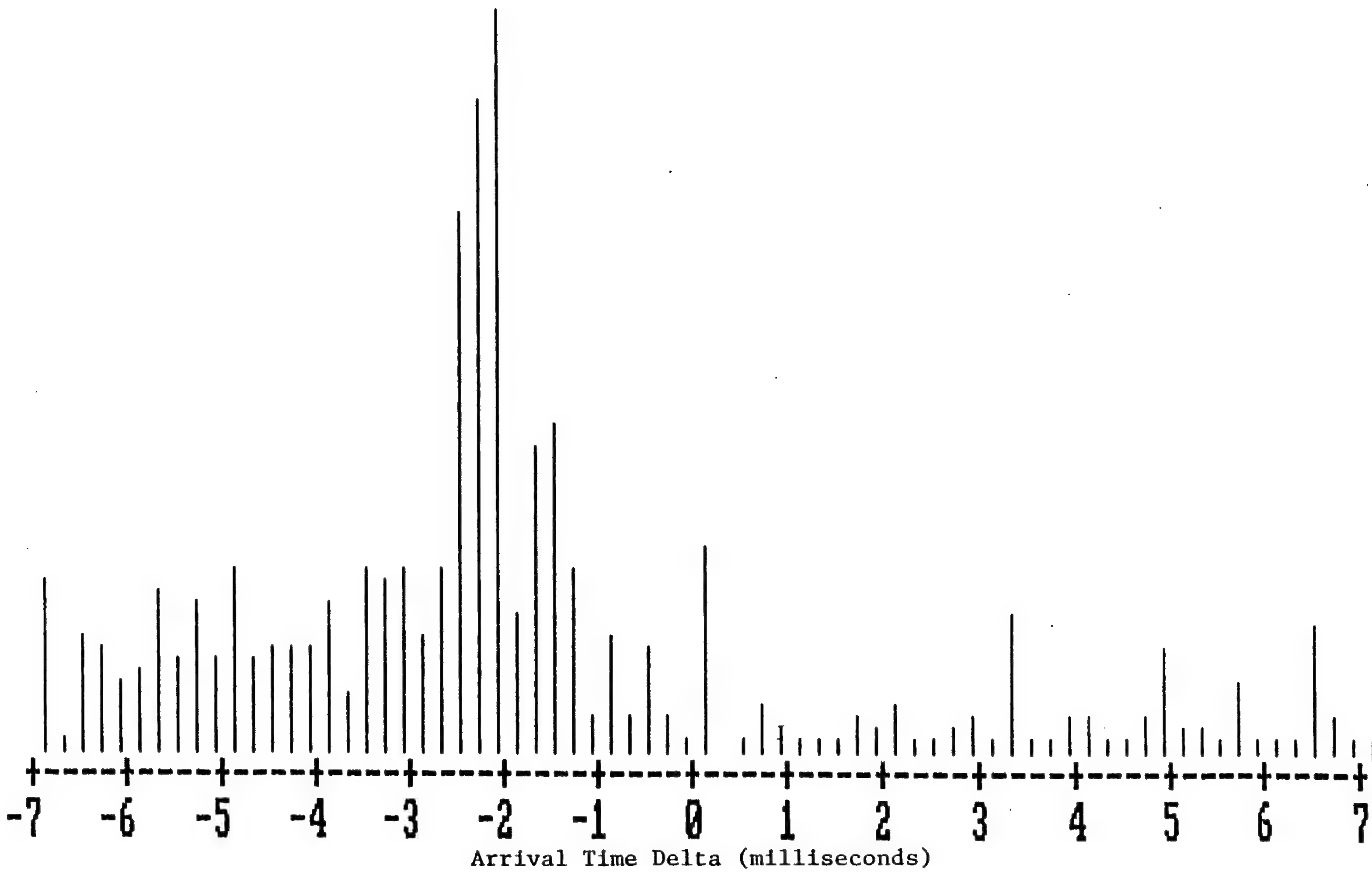


Figure 2. Leak location example showing actual location of 0.014-inch-diameter leak

SECTION III

TEST FIXTURES DESIGN

A. CRITERIA

The leak-test fixtures were designed to permit evaluation of methods, hardware, and software, and to generate test data which might indicate the feasibility of using AE technology to detect small leaks in USTs.

Although the U.S.A.F. fuel tanks are reportedly buried in a sand blanket, some may have been buried in silty or clayey soils. Thus sandy, silty, and clayey soils were used in the test program in order to determine whether or not the interaction of the leak turbulence with the surrounding soil and the containment wall would cause different acoustic leak signals for each soil type.

A UST is typically 10-to 12-feet in diameter and 60-to 90-feet in length. The soil depth (to the top of tank) reportedly varies between 2 and 20 feet. Manways and inlet/outlet pipes connected to the tank provide access for sensor attachment.

Thus, a leak on the bottom of the tank may have between 12 and 32 feet of pressure head if the fuel level is at ground surface. A leak on the top of the tank may have from 2-to 20-feet of head. The fuel level can be lowered below the ground level, or possibly extended above ground level using a standpipe, such as is done in testing gas-station underground tanks.

No laboratory-scale test apparatus can simulate precisely the acoustic characteristics of these UST's. A leaking coffee-can buried under six inches of soil appears to be as good a simulation as a leaking 42-gallon barrel buried under six feet of soil. For these tests, however, a larger container was needed in order to evaluate and perfect the location software (by discerning distinct leak locations).

B. DESCRIPTION

The primary test apparatus is shown in Figure 3. It consists of a 20-foot length of 1.5-inch-diameter steel pipe placed horizontally a few inches above the floor. An inventory supply system was suspended on a pulley which allowed variable elevations (0-15 feet) to be occupied above the test pipe. The section of test pipe with the leak source was buried in a soil box. A small industrial drill (No. 80) was used to drill a 0.014-inch-diameter hole in the pipe. A 0.021-inch-diameter hole was made with a larger drill. In addition, a smaller leak passage was made by using a No. 4 screw in a drilled and tapped No. 4 screw hole. The hole was drilled on the upside tolerance so that a No. 4 screw had a loose fit. Some water leakage occurred with the screw tightened; partial unscrewing of the screw caused increasing amounts of leakage.

A second test apparatus having a 0.025-inch-diameter leak hole (Figure 4) was used for the JP-4 fuel tests. This larger leak gave a steady leak signal which was easily measurable using the digital readout of the AELL-2000 instrument.

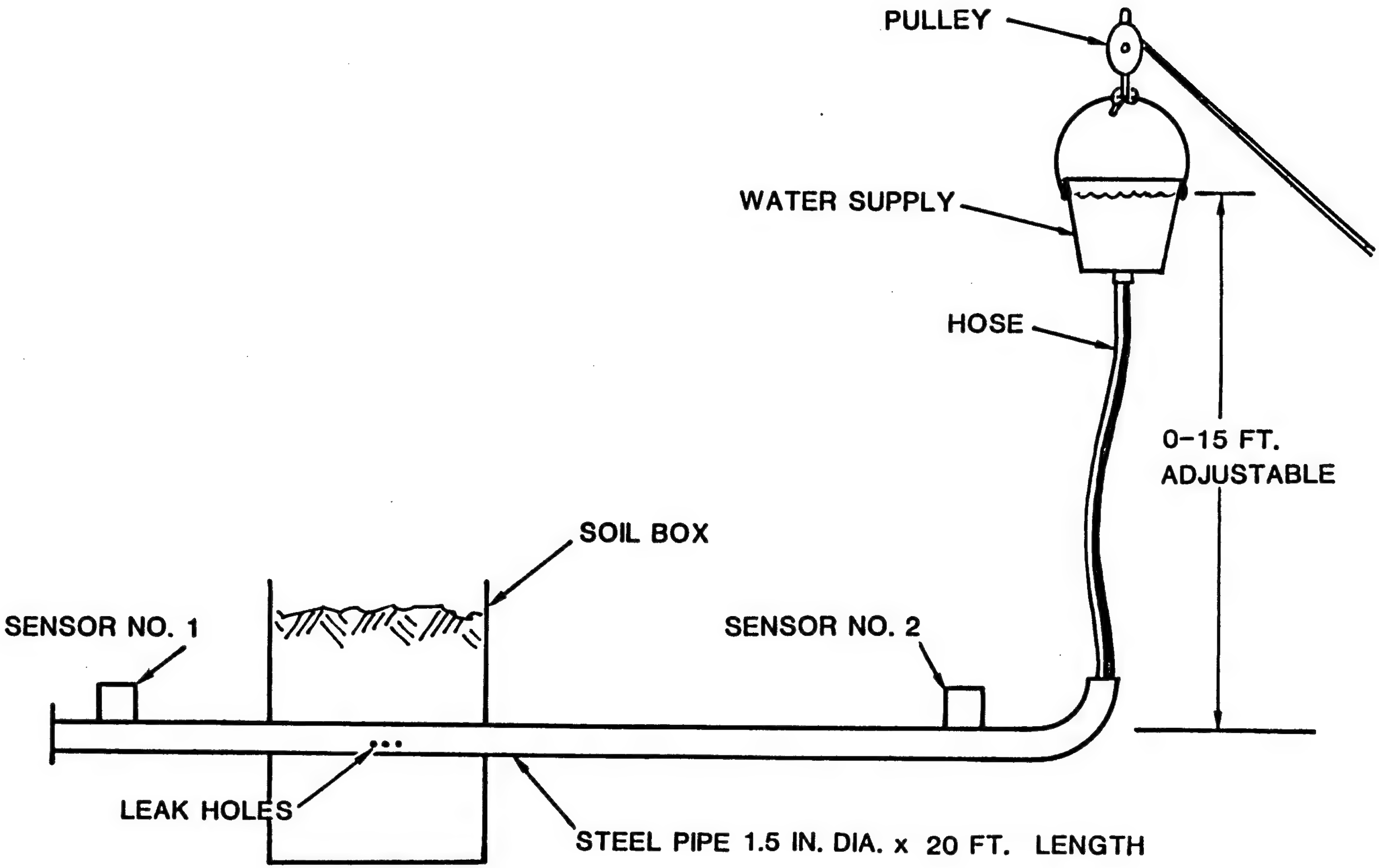


Figure 3. Leak test fixture used for activity-detection and location-detection tests

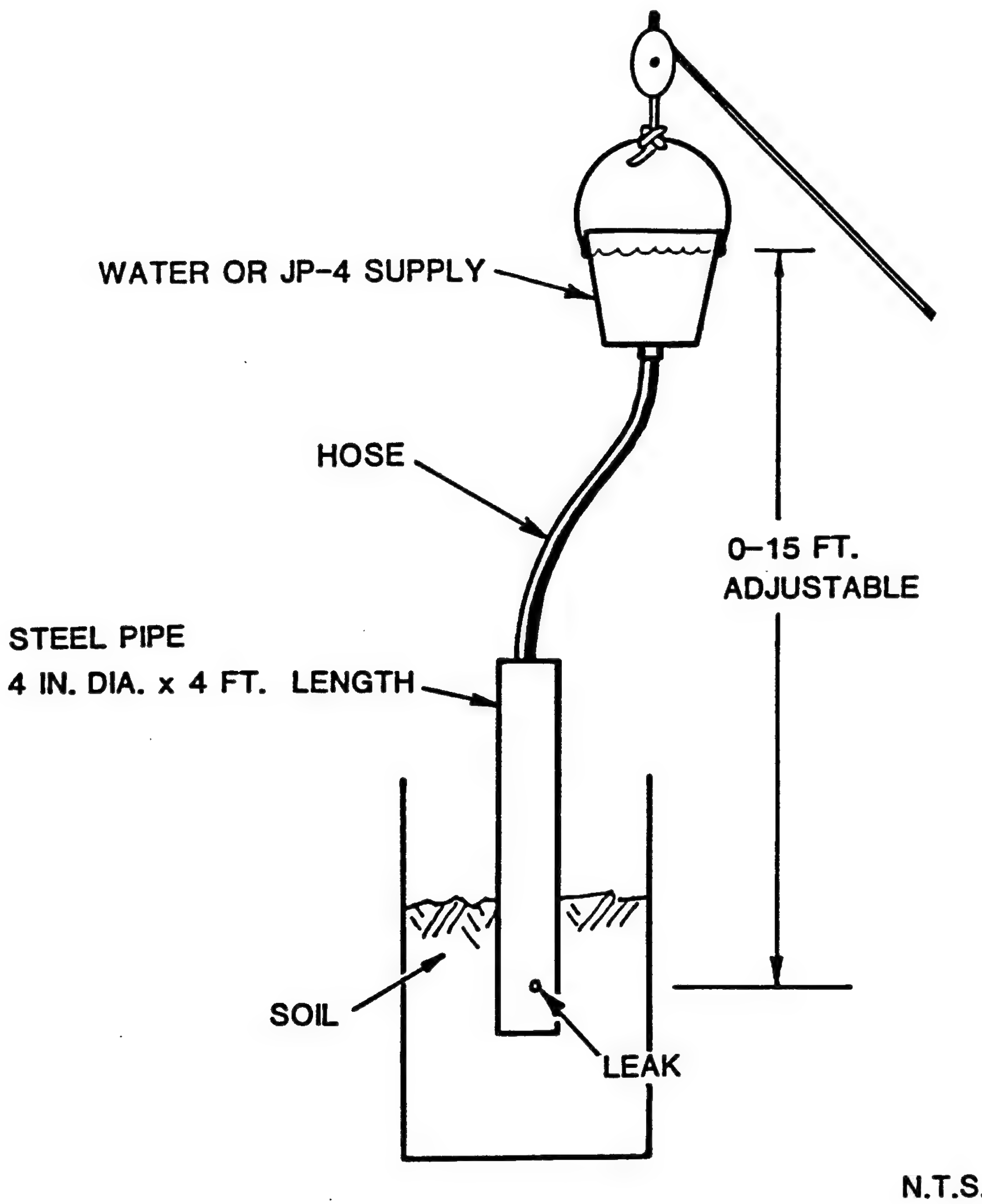


Figure 4. Leak test fixture used for JP-4, water, and gasoline tests

SECTION IV

TEST DATA

A. FORMAT

Statistical data are output by the STATS program in the tabular form of Table 1, and location data are output by the LOCATE and PEAKSORT programs as shown in Figure 2. Some of these data were then transferred to a LOTUS worksheet. Figures 5 through 25, and 46 were plotted directly from the worksheet. Figures 26 through 45 were printed directly from the video screen at the time of testing.

B. VARIABLES

The majority of testing was done using the test setup shown in Figure 3. For the "location" testing, acoustic-emission sensors were located at positions 1 and 2. For the "statistical" testing, an acoustic-emission sensor was located at position 1, and the accelerometer was located at position 2.

The three types of leaks used were located in a six-inch-long section of pipe as shown. Each test involved only one leak at a time; the other two holes were sealed by a rubber gasket/hose clamp arrangement.

Sand, silt and clay were variously used to cover the immediate area of the leak hole during testing. Leakage water was allowed to drain from the soil container into a pan immediately below. The soil remained saturated with water during testing. With 12-15 feet of pressure head, the leak would quickly form its own cavity, i.e. void of water and soil particles. The leakage rate was not reduced by back-pressure in this cavity.

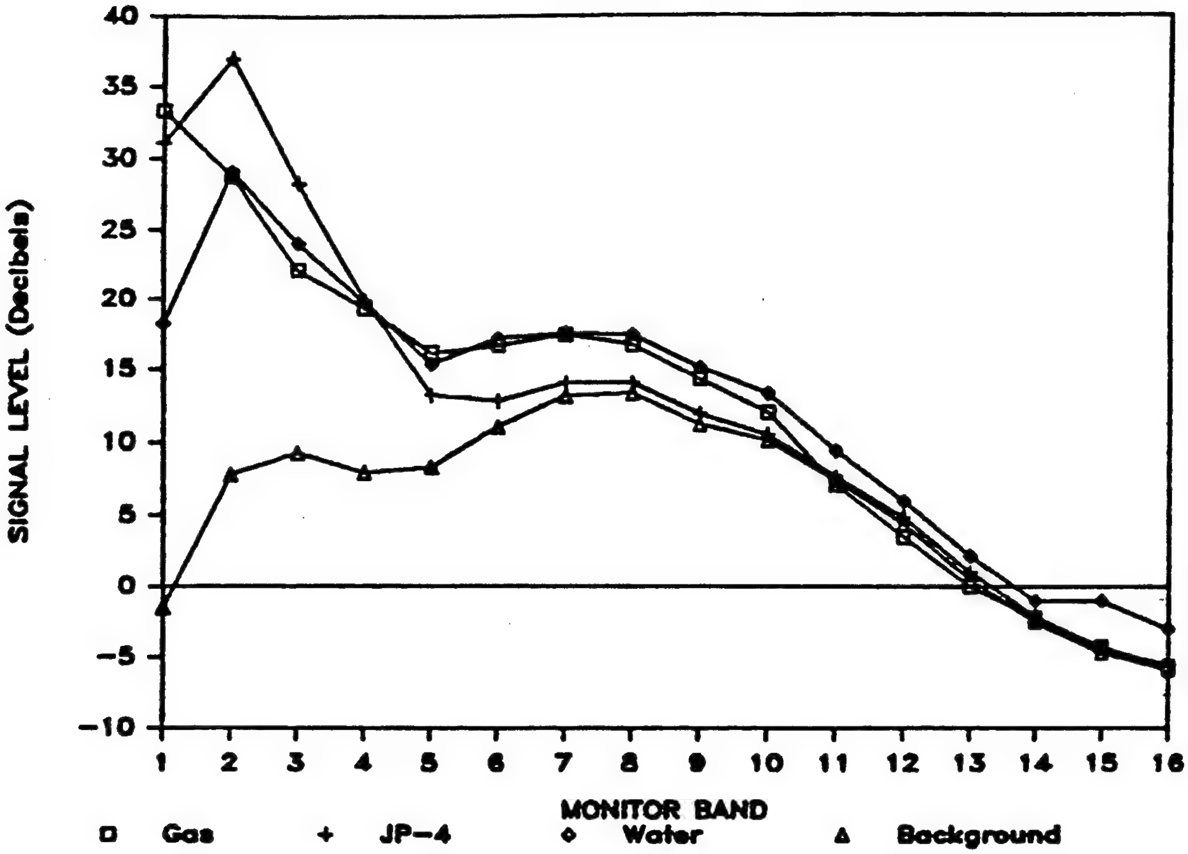


Figure 5. Leak spectra for JP-4, water, and gasoline

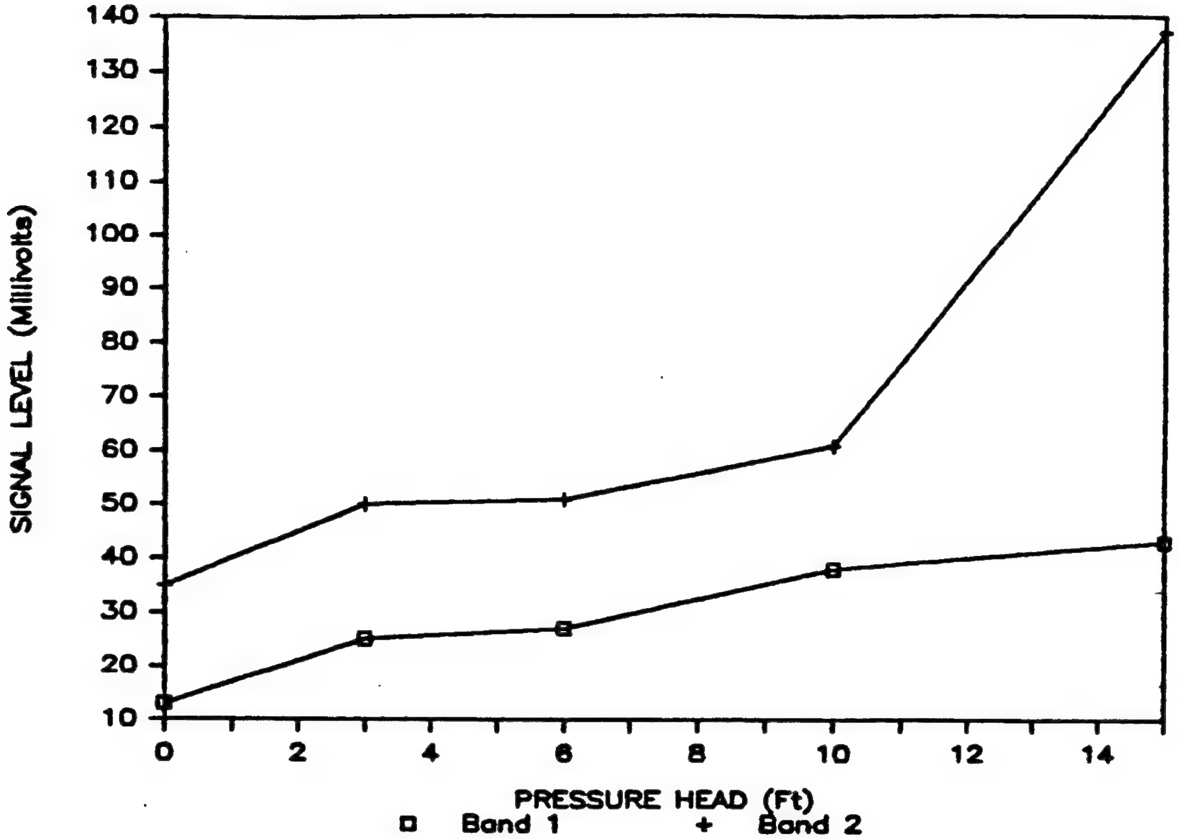


Figure 6. Signal averages for 0.014-inch-diameter leak in sandy soil

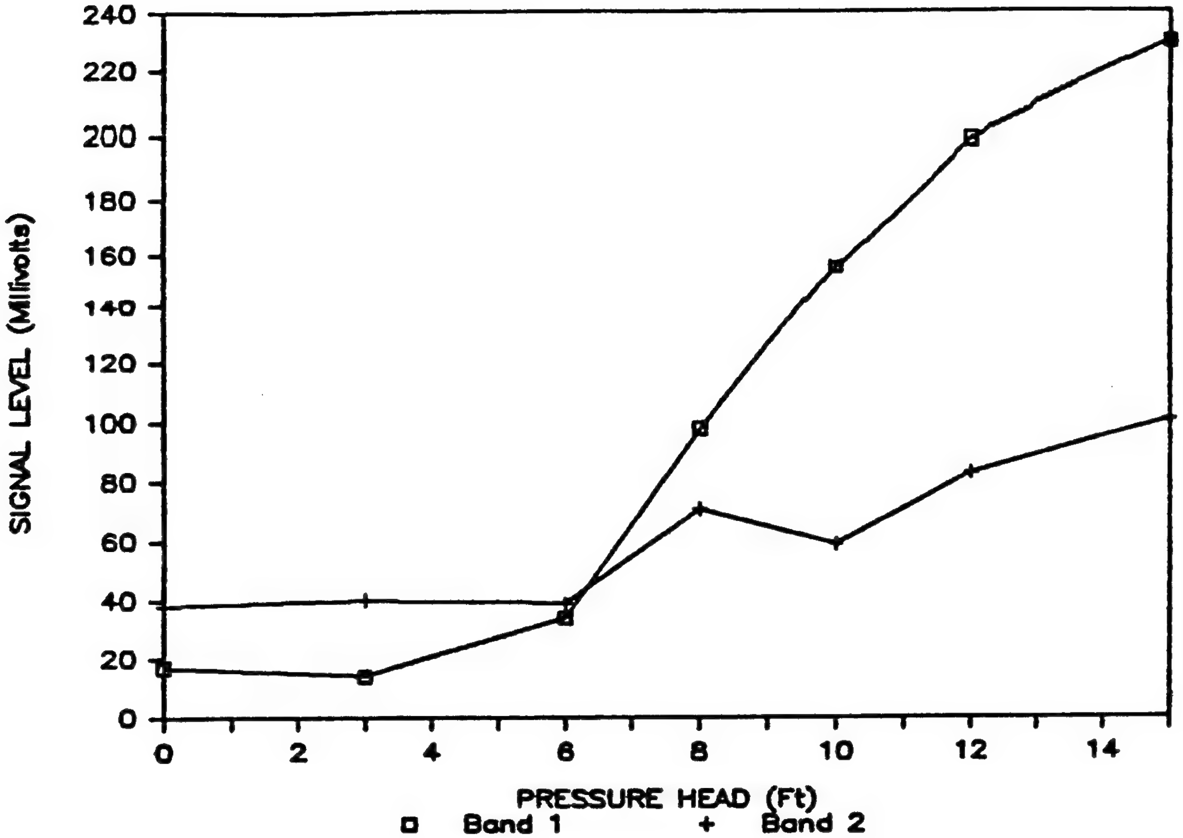


Figure 7. Signal averages for 0.021-inch-diameter leak in sandy soil

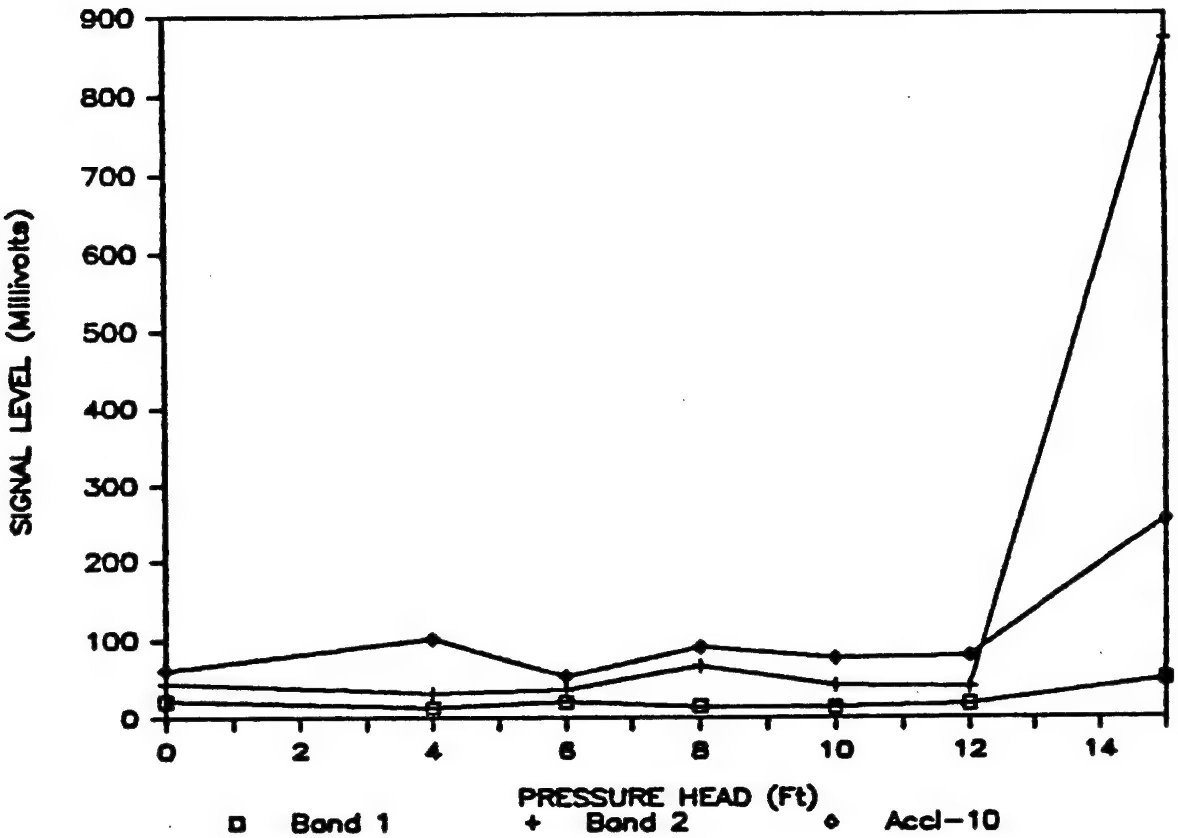


Figure 8. Signal averages for 0.014-inch-diameter leak in silty soil

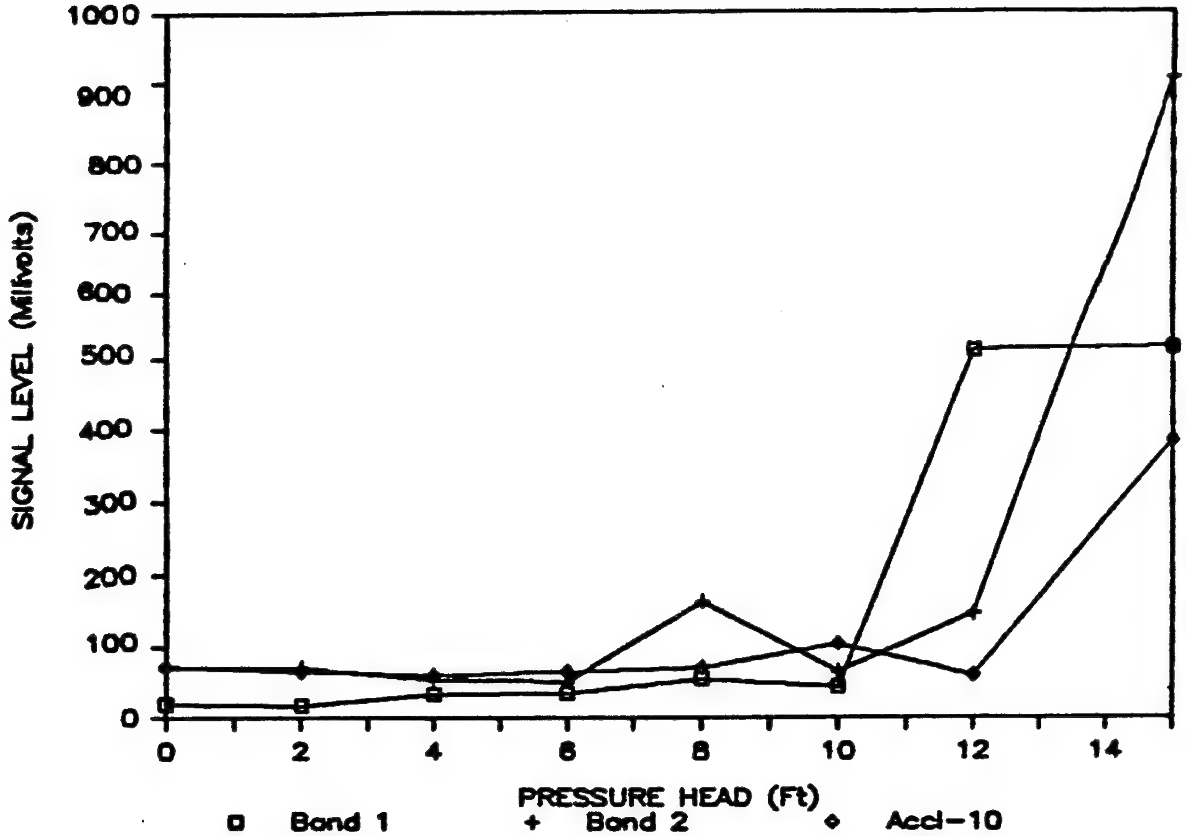


Figure 9. Signal averages for 0.021-inch-diameter leak in silty soil

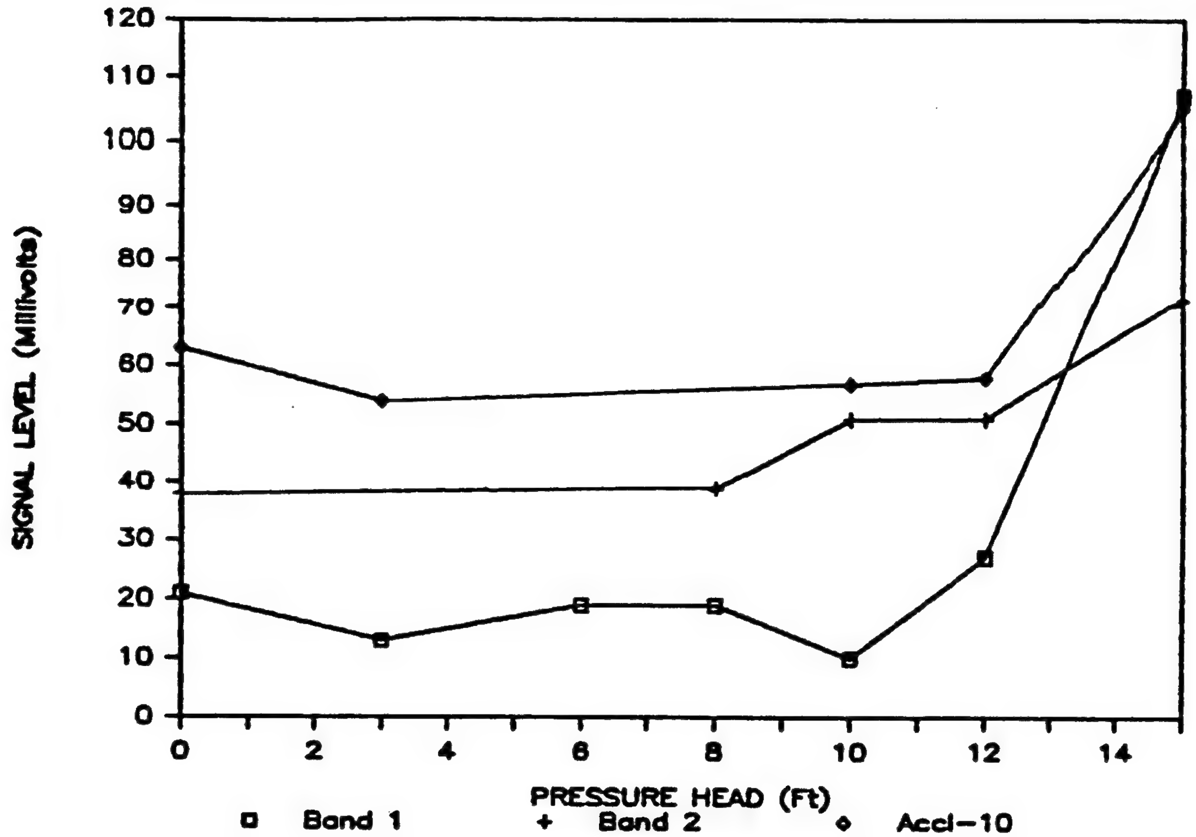


Figure 10. Signal averages for 0.014-inch-diameter leak in clayey soil

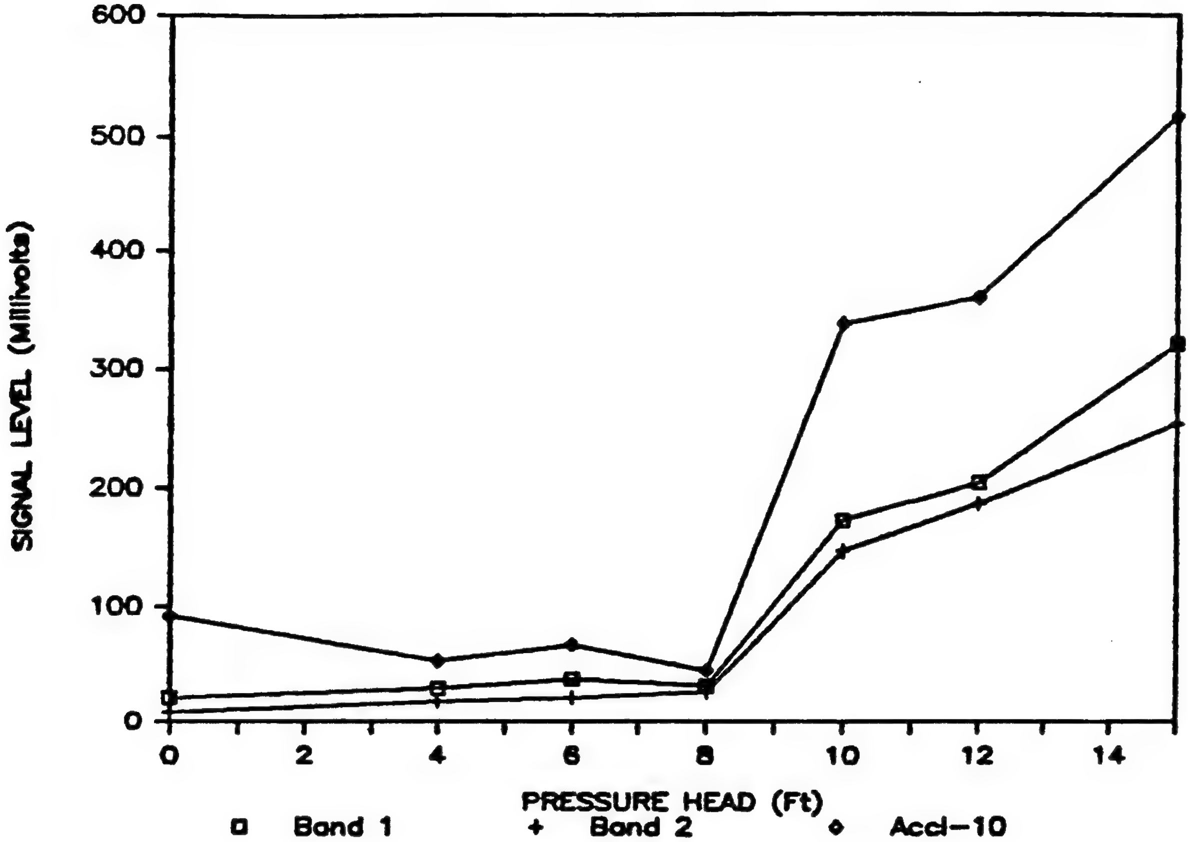


Figure 11. Signal averages for 0.021-inch-diameter leak in clayey soil

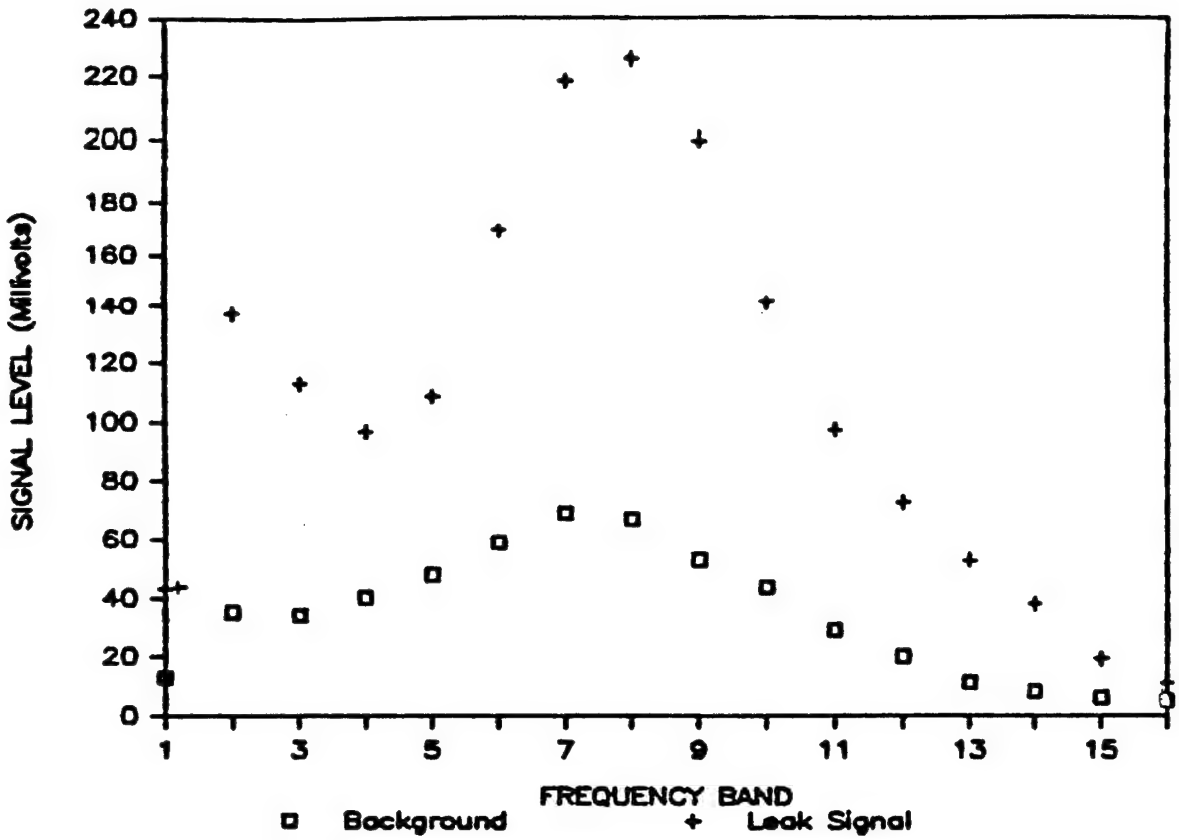


Figure 12. Acoustic emission spectrum for 0.014-inch-diameter leak in sandy soil

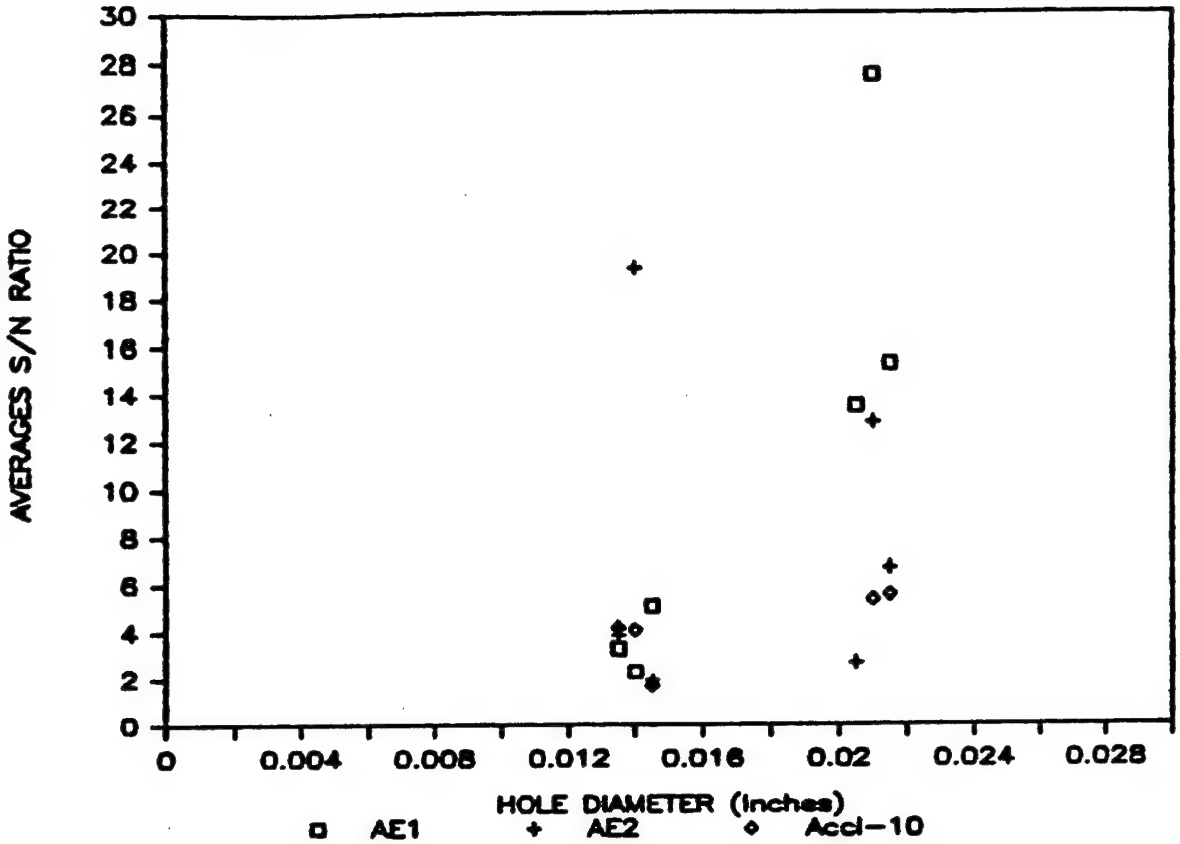


Figure 13. Signal averages S/N ratios for 0.014- and 0.021-inch-diameter holes

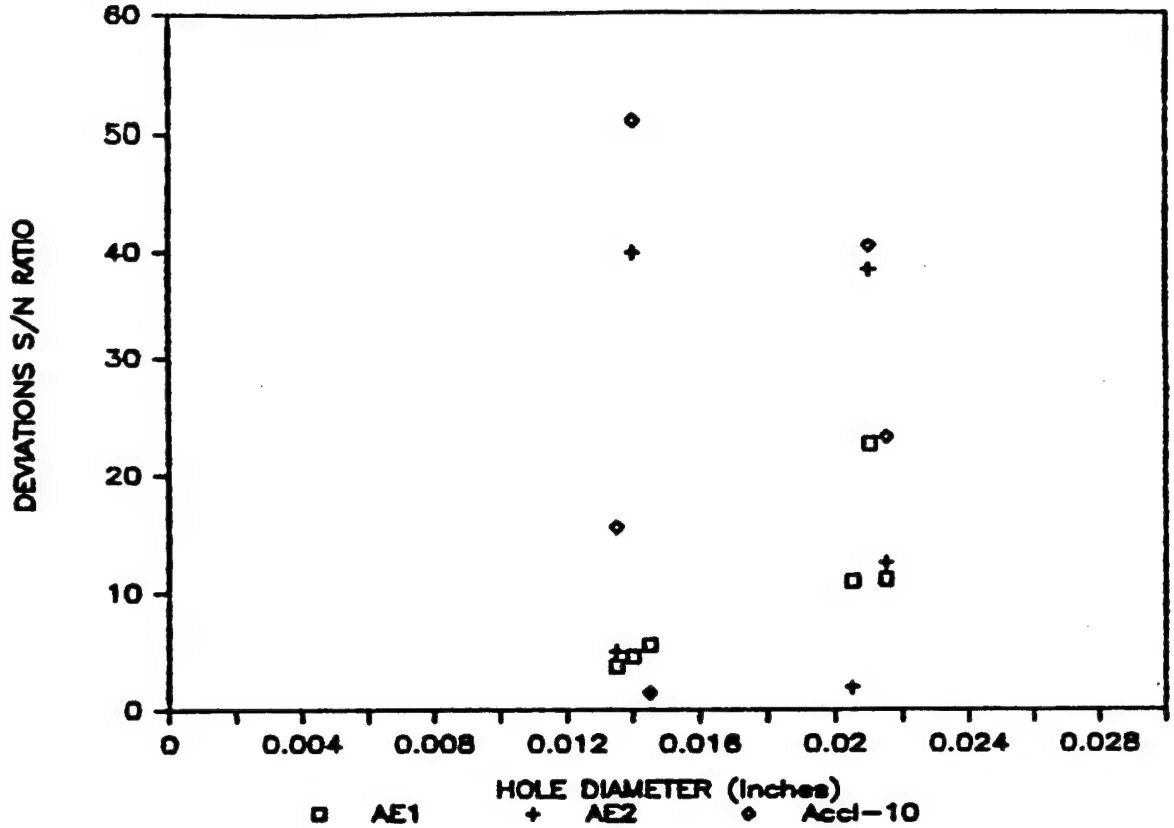


Figure 14. Signal standard deviations S/N ratios for 0.014- and 0.021-inch-diameter holes

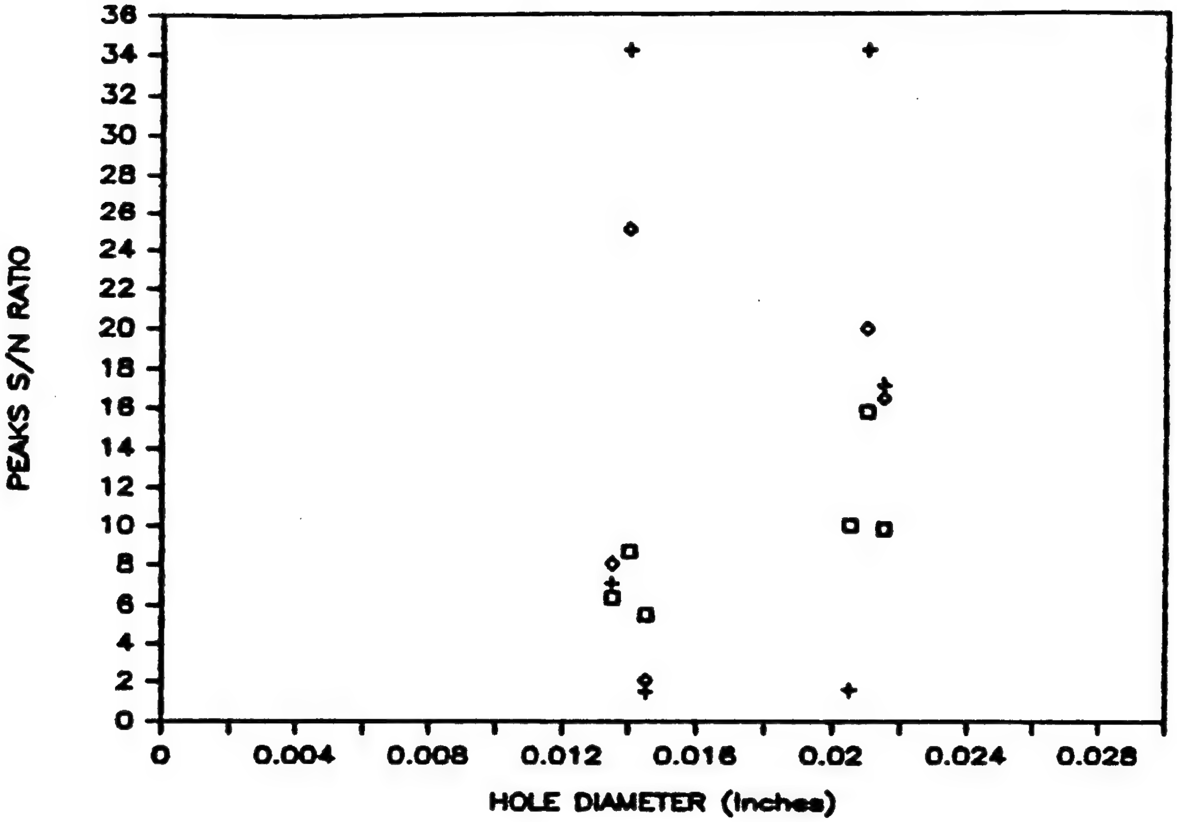


Figure 15. Signal peak S/N ratios for 0.014- and 0.021-inch-diameter holes

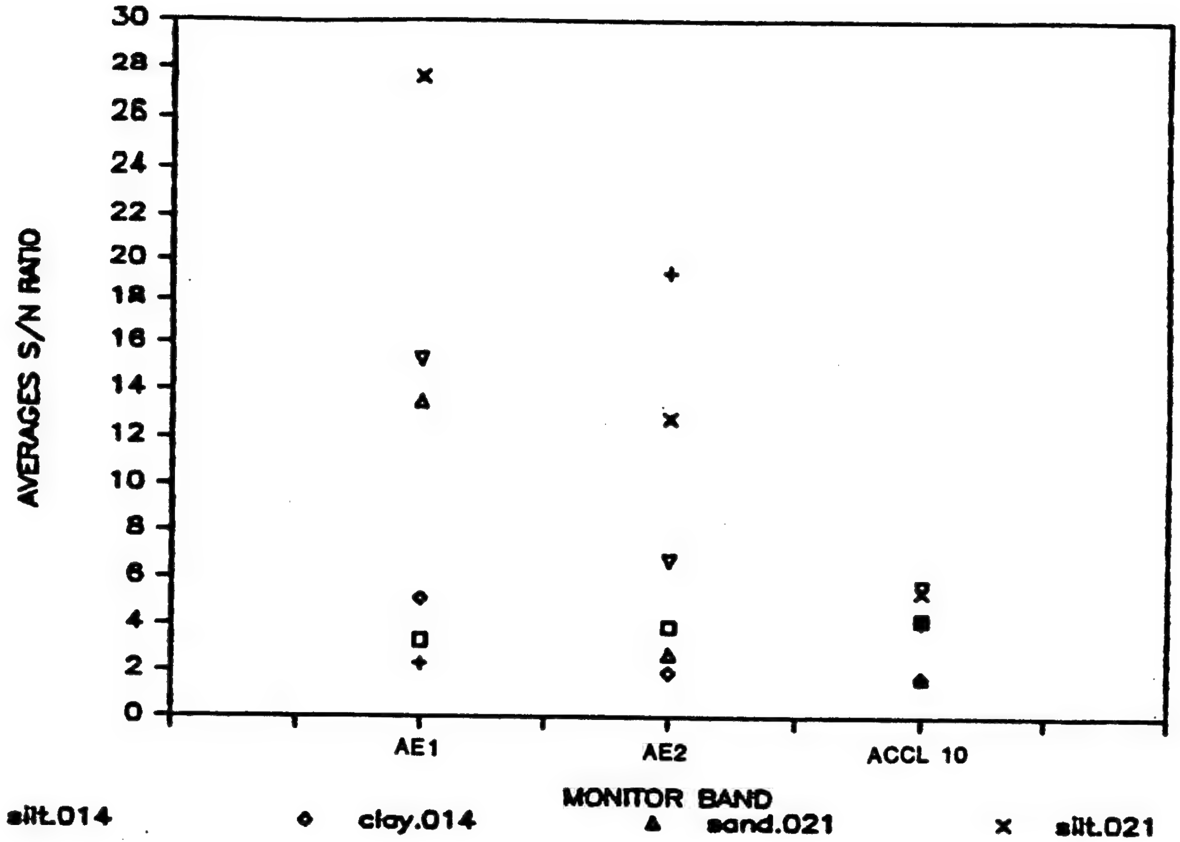


Figure 16. Signal averages S/N ratios for three selected monitor bands

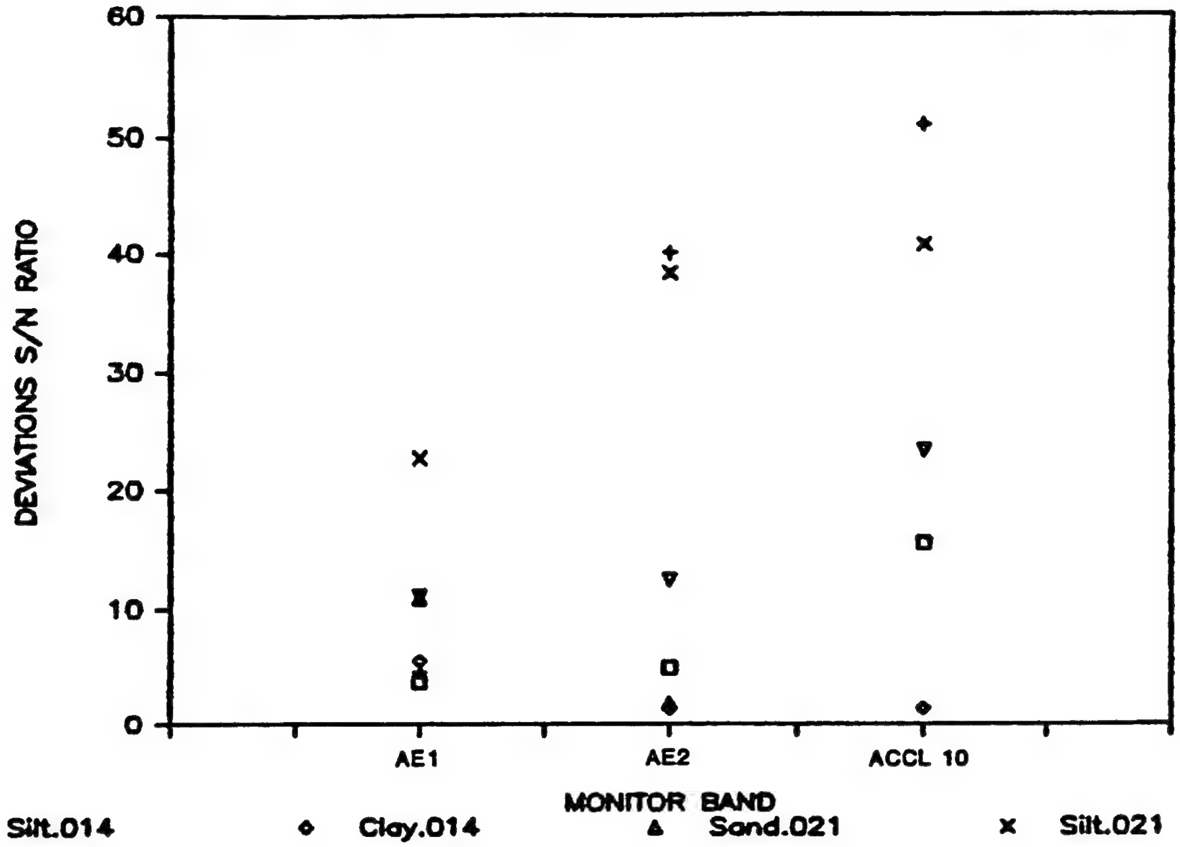


Figure 17. Signal standard deviation S/N ratios for three selected monitor bands

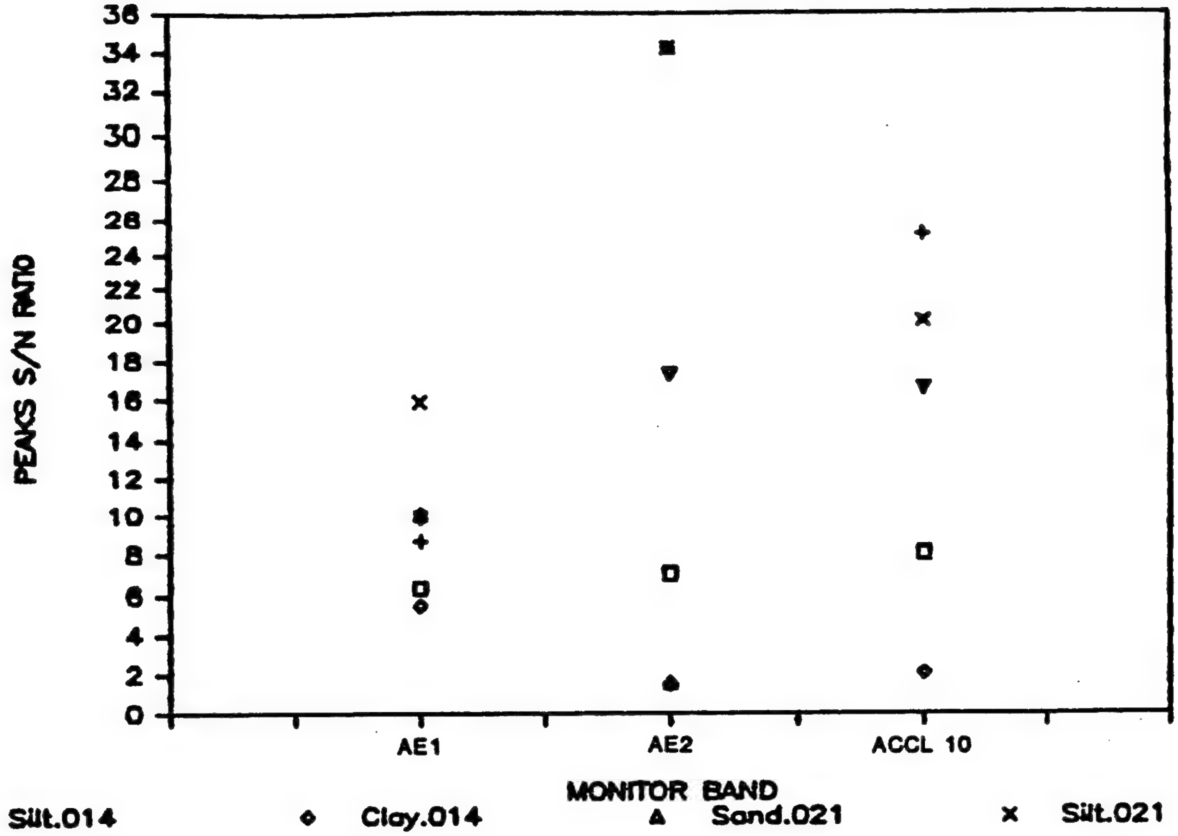


Figure 18. Signal peak S/N ratios for three selected monitor bands

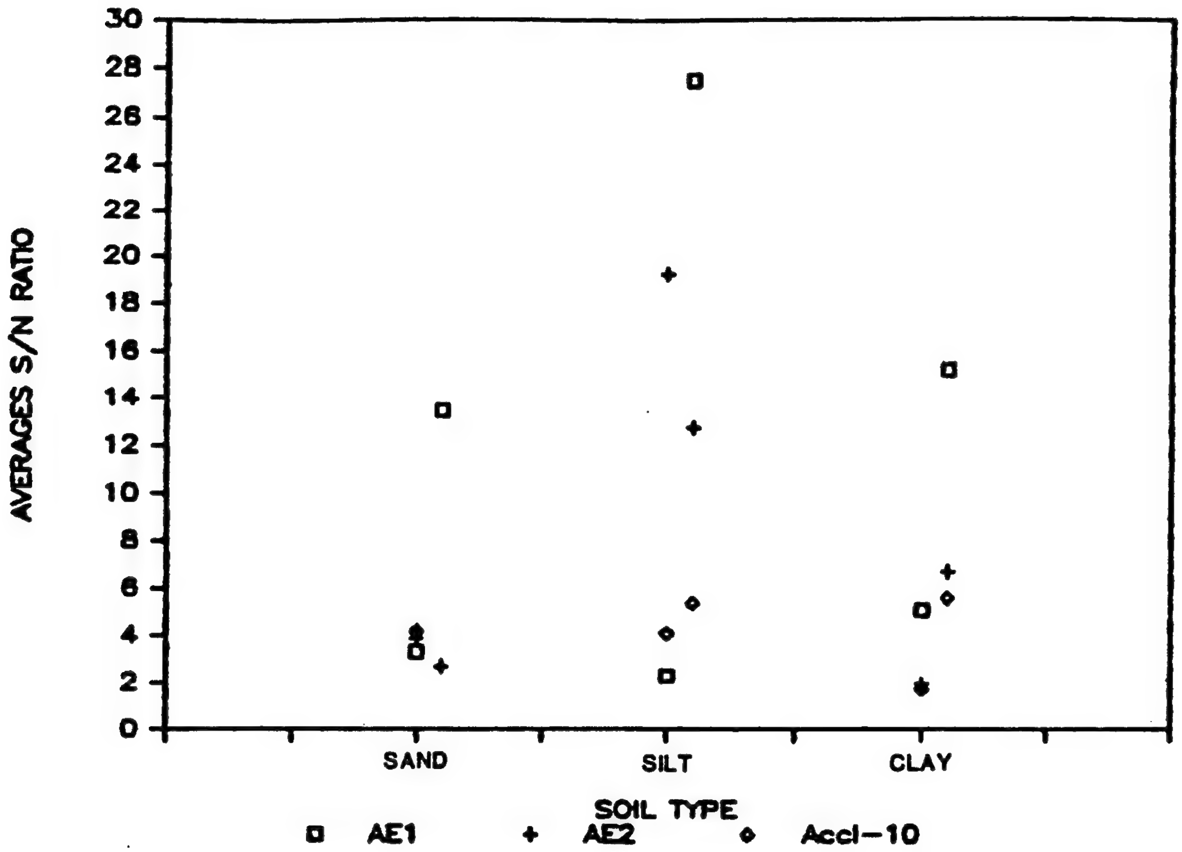


Figure 19. Signal averages S/N ratios for the tested soil types

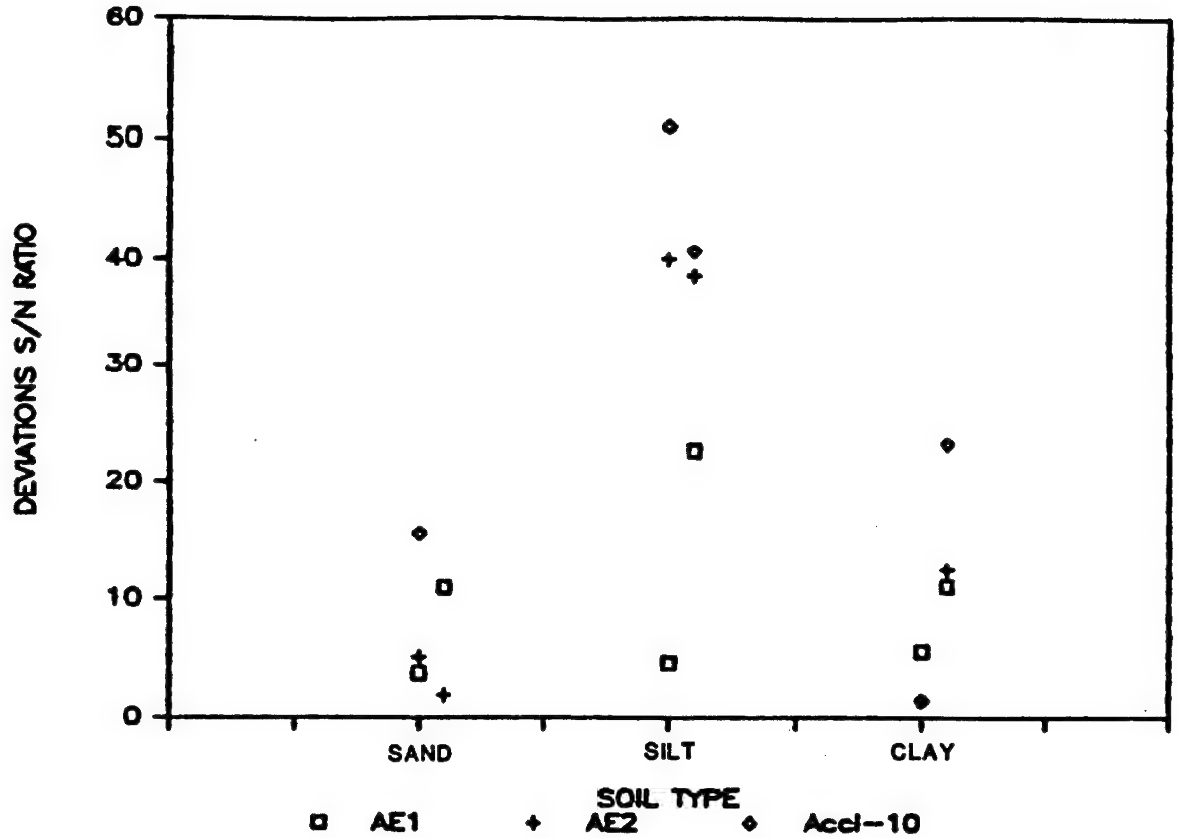


Figure 20. Signal standard deviations S/N ratios for the tested soil types

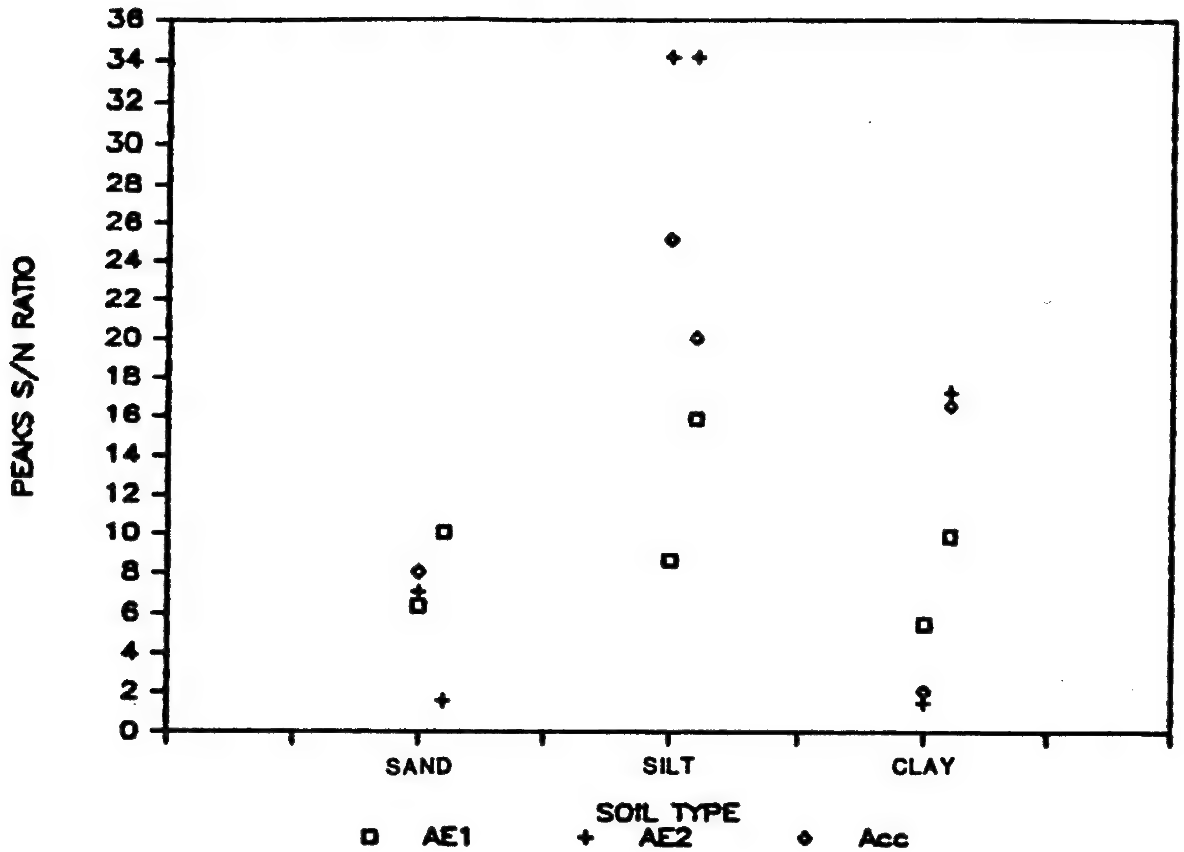


Figure 21. Signal peak S/N ratios for the tested soil types

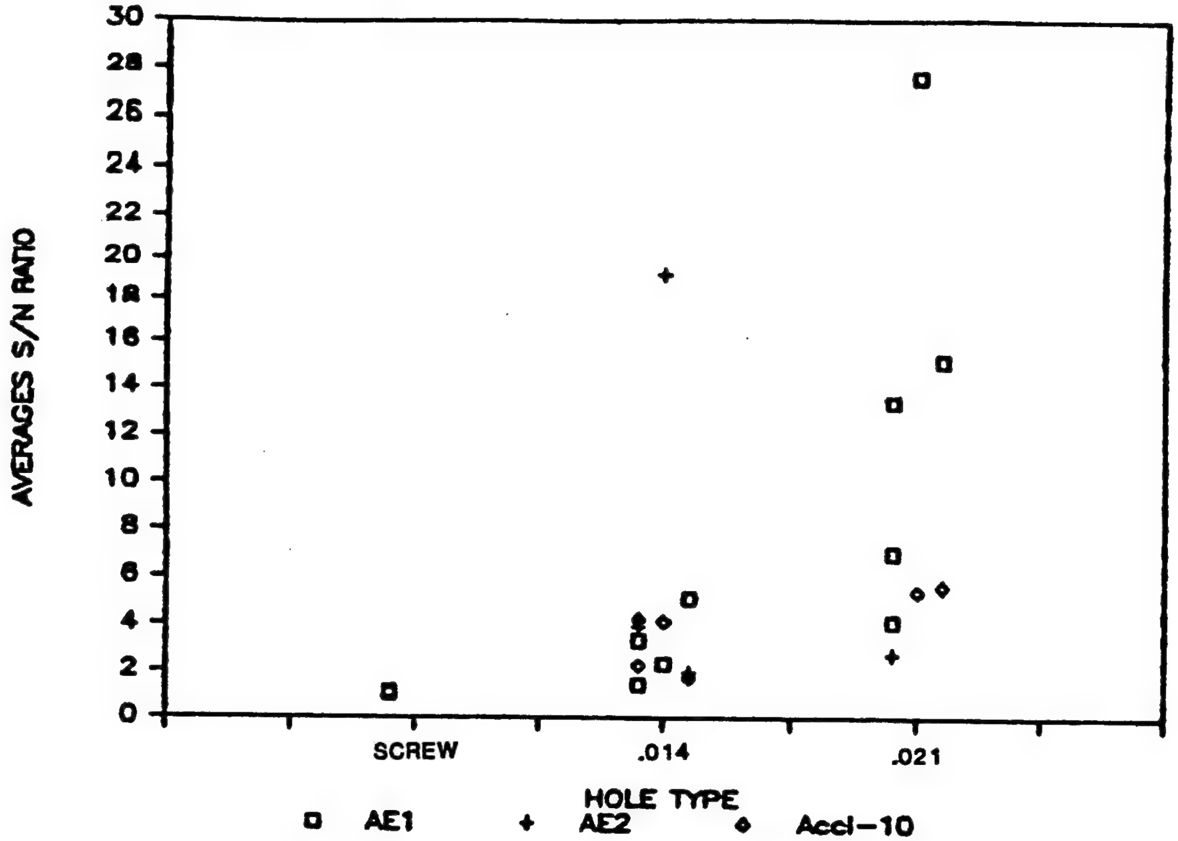


Figure 22. Signal averages S/N ratios for combined data

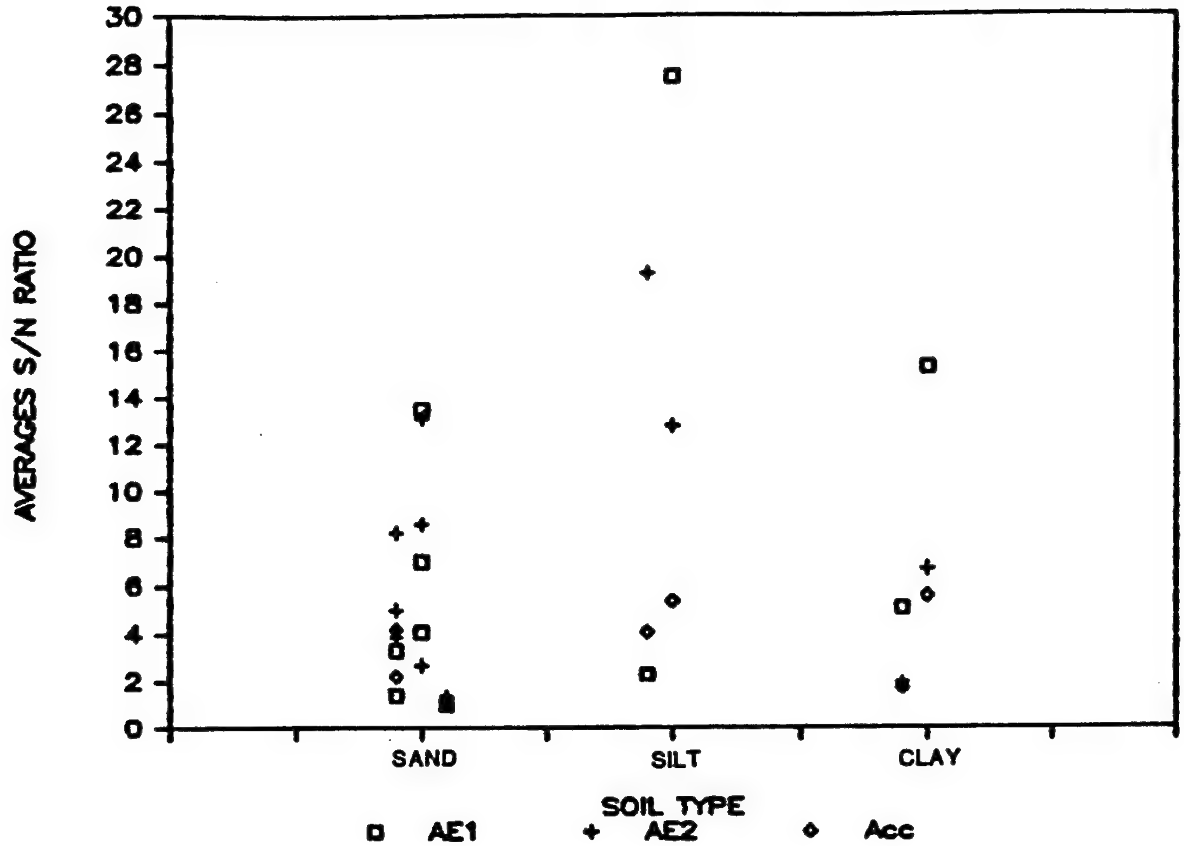


Figure 23. Signal averages S/N ratios for combined data vs soil type

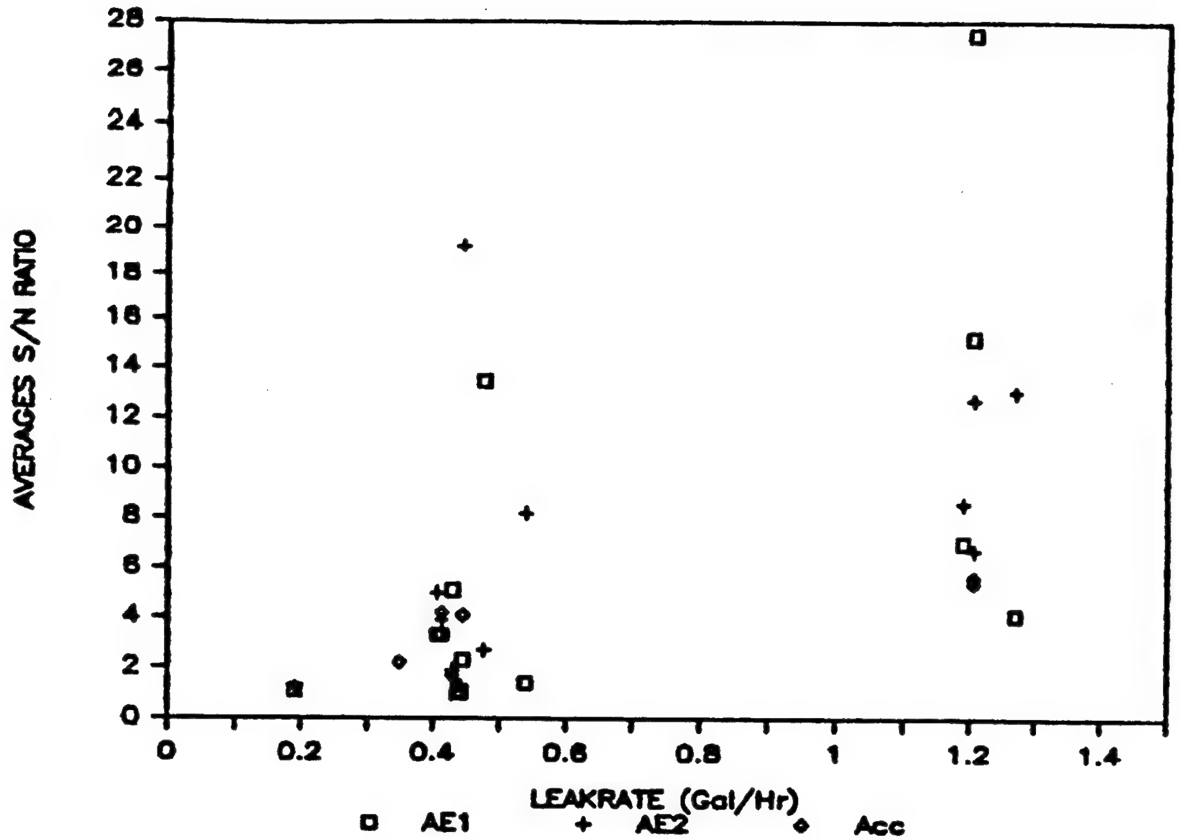


Figure 24. Combined data signal average ratios as function of leak rate

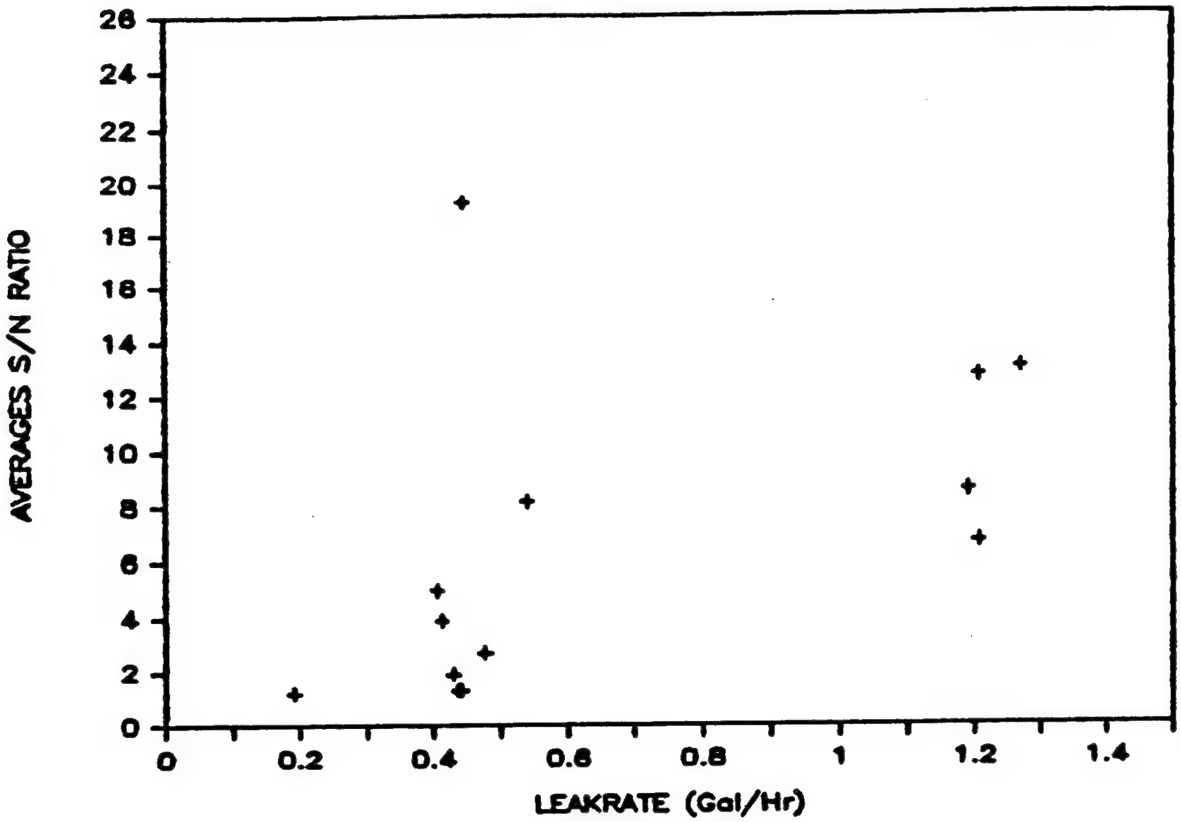


Figure 25. Band 2 signal average ratios as function of leak rate

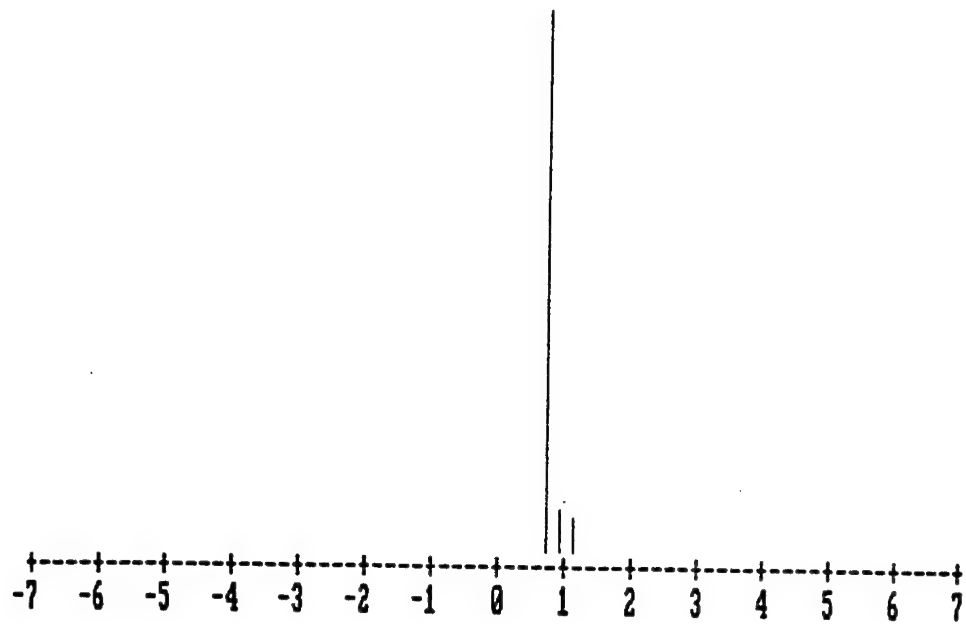
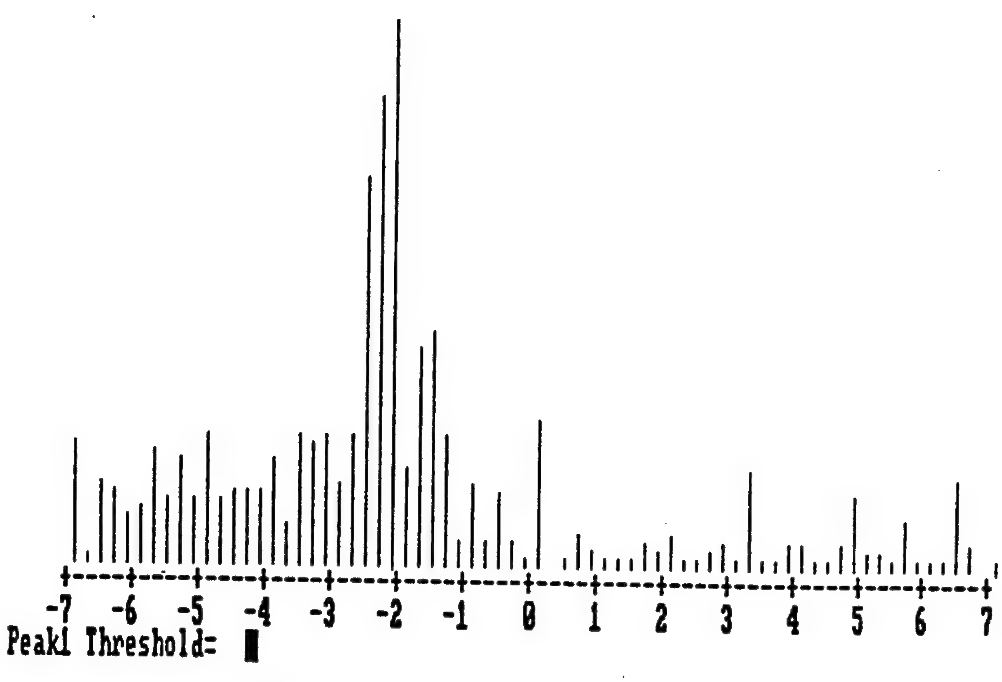


Figure 26. High-resolution location of acoustic pulser



Delta-Arrival-Time (milliseconds)

Figure 27. Location data for 0.014-inch-diameter hole using events above 0.3-volts peak

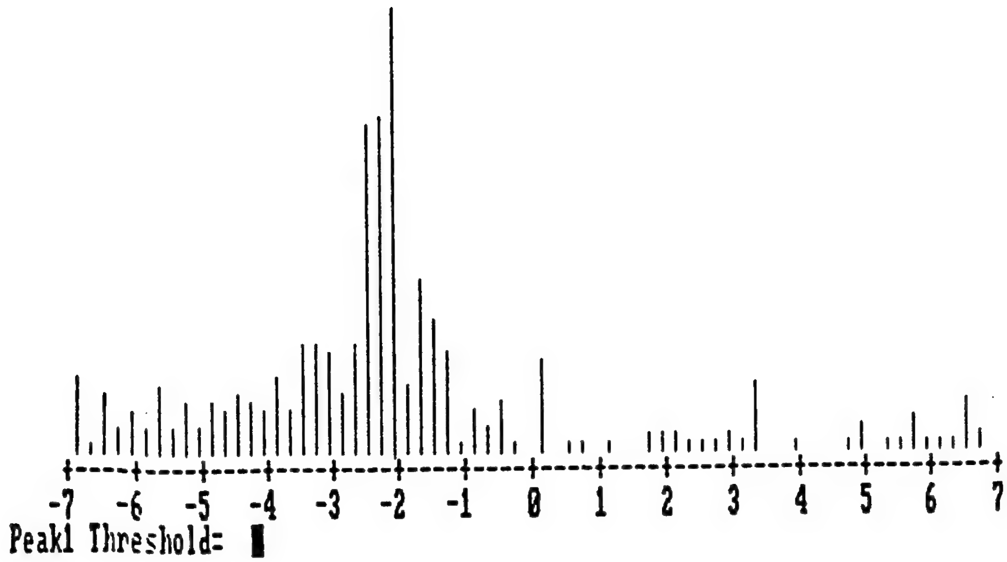
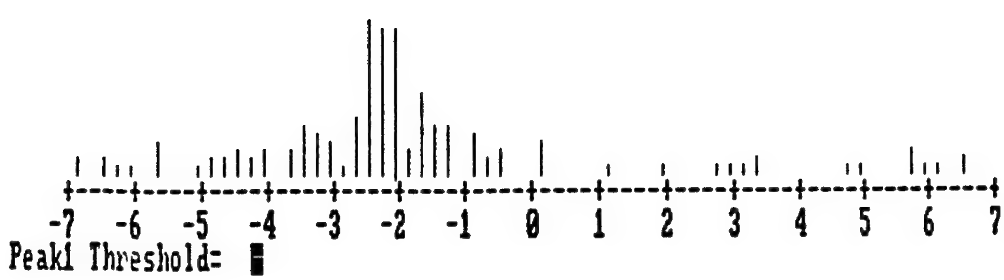


Figure 28. Location data for 0.014-inch-diameter leak using events with greater than 1.0-volts peak



Delta-Arrival-Time (milliseconds)

Figure 29. Location data for 0.014-inch-diameter leak using events with greater than 2.5-volts peak

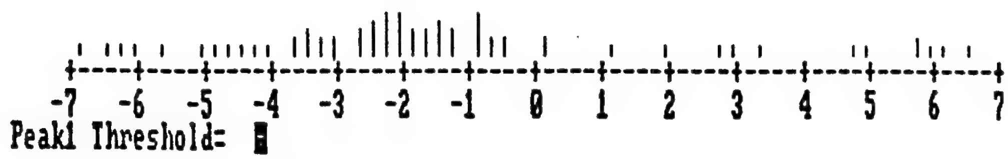


Figure 30. Location data for 0.014-inch-diameter leak using events with greater than 4.95-volts peak

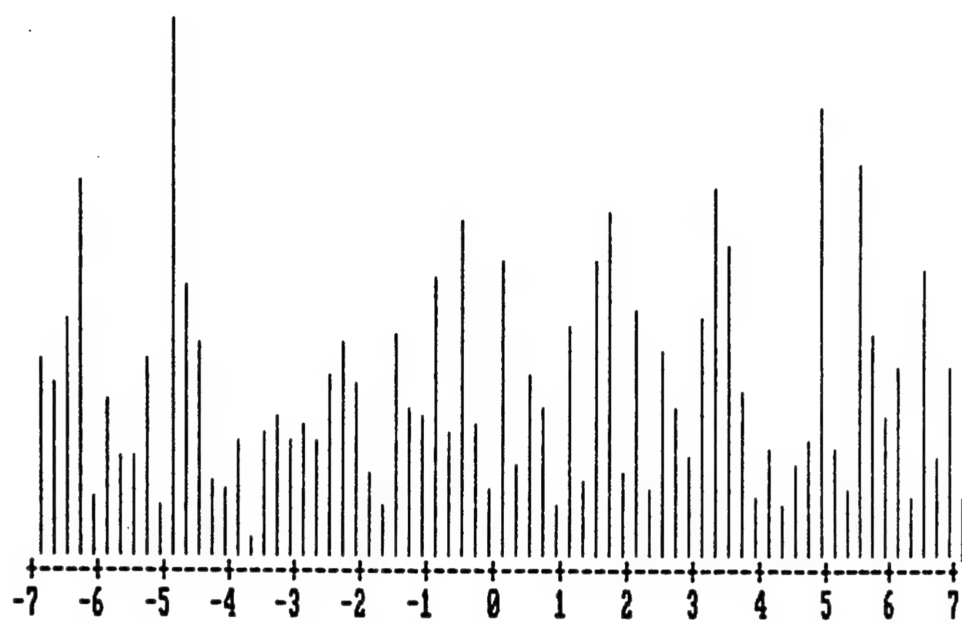
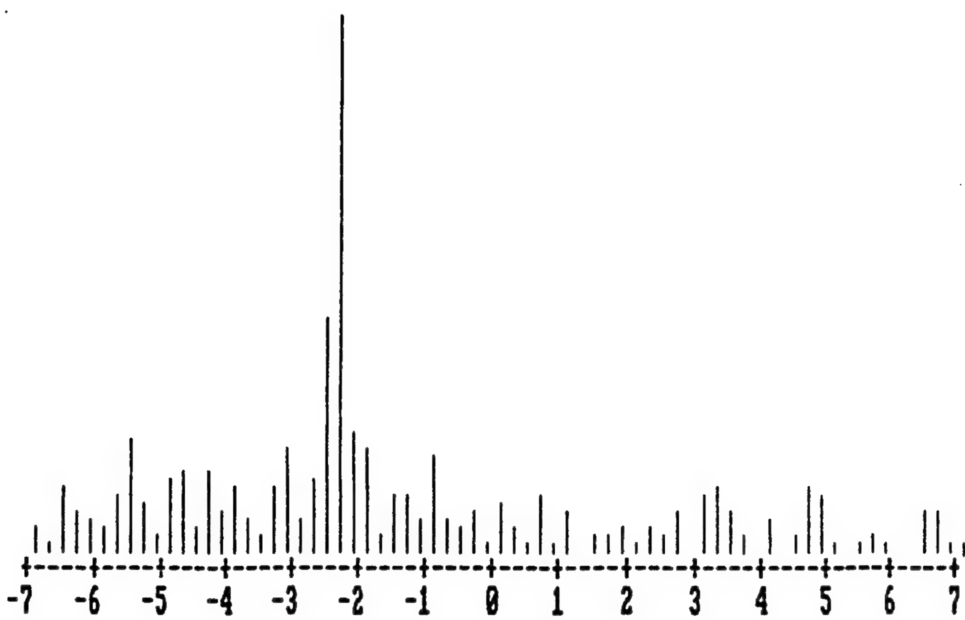


Figure 31. Random location data for noise background using all events

Figure 32. Random location data for noise background using events greater than 0.4 volts



Delta-Arrival-Time (milliseconds)

Figure 33. Sharp resolution location for 0.014-inch-diameter leak using all events

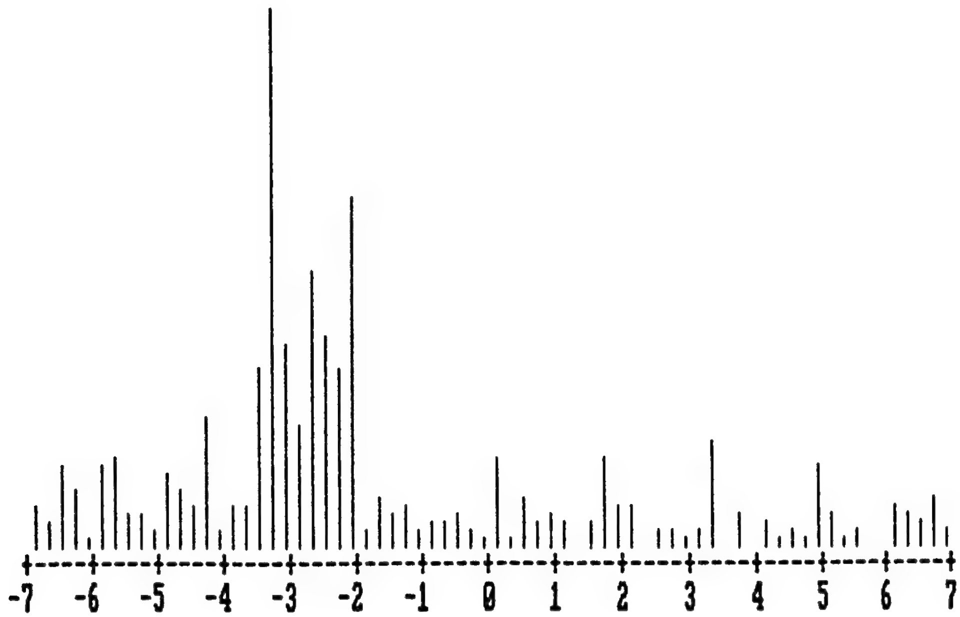


Figure 34. Resolution of location of 0.014-inch-diameter leak using Band 1

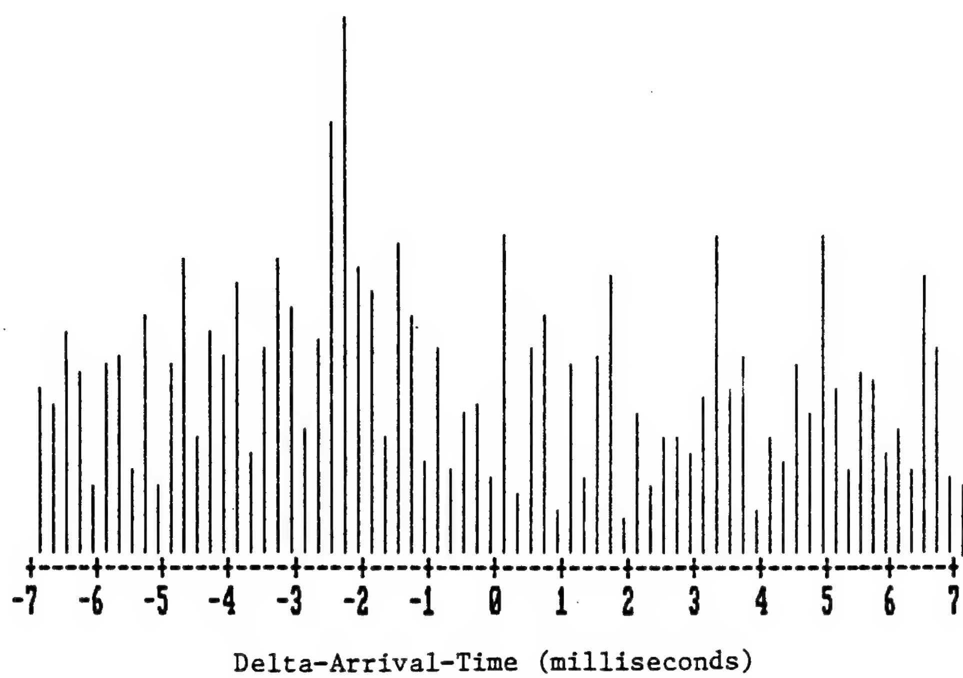


Figure 35. Low S/N location of 0.014-inch-diameter leak for all events

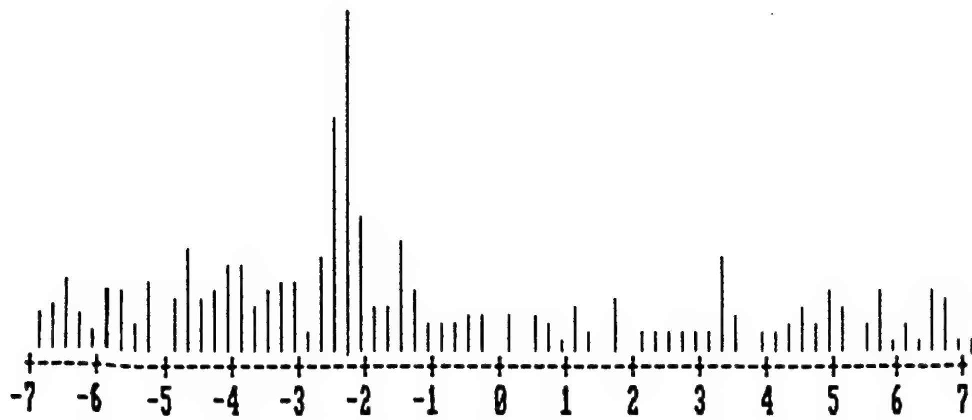


Figure 36. Improved S/N for Figure 35 leak using only events greater than 0.5-volts peak

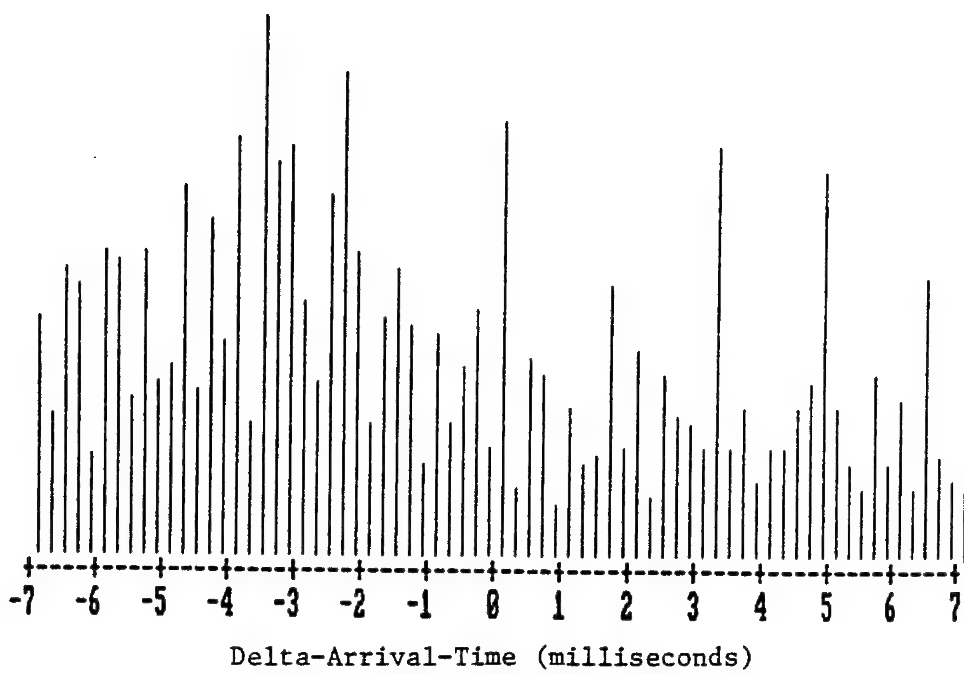


Figure 37. Low S/N location of loose-screw leak using all events

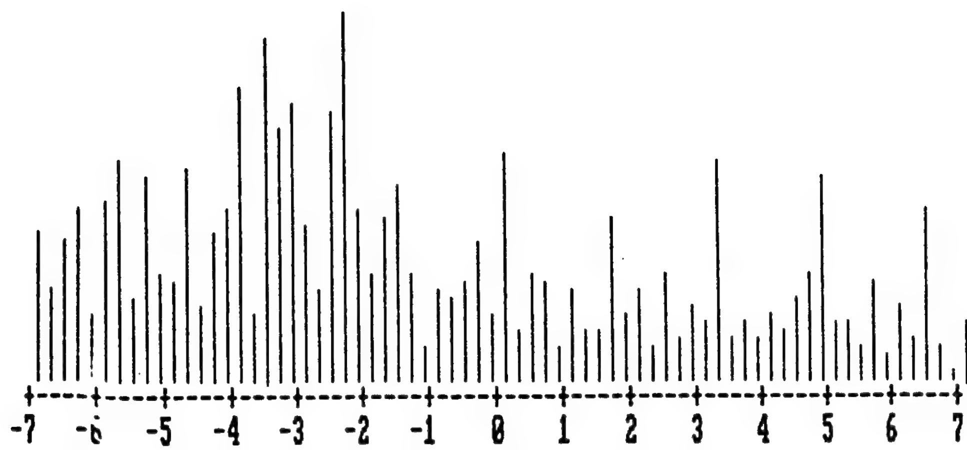


Figure 38. Slightly improved S/N for Figure 37 peak

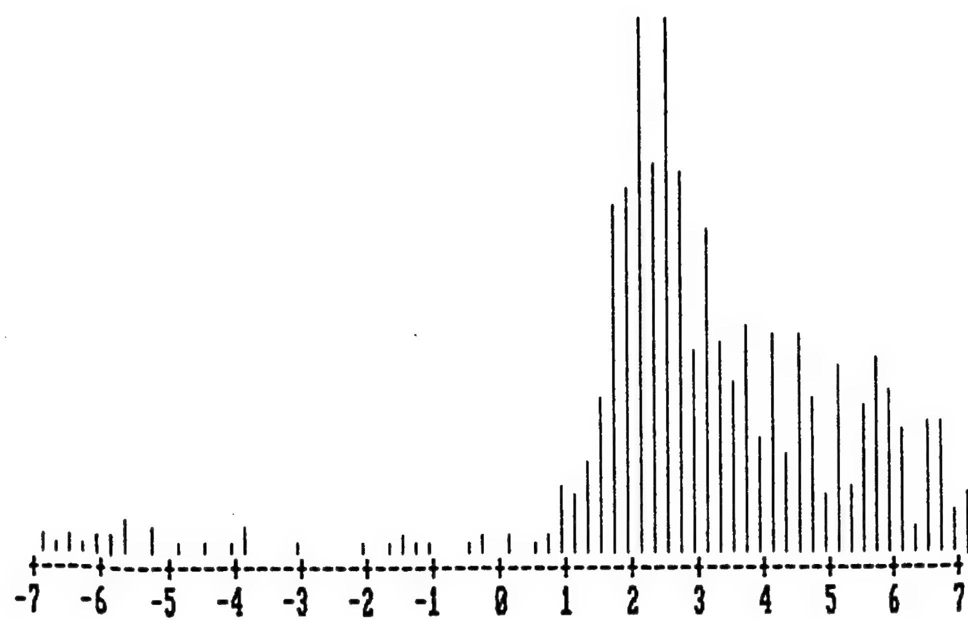


Figure 39. Reversed sensor leads location for loose-screw leak

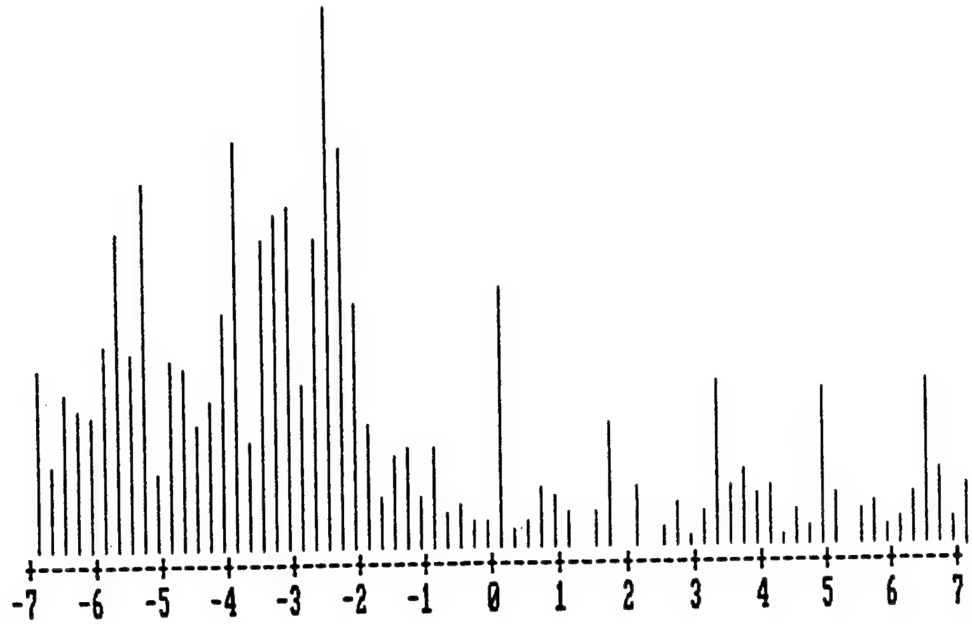


Figure 40. Lowest flow-rate leak located (gal/hr)

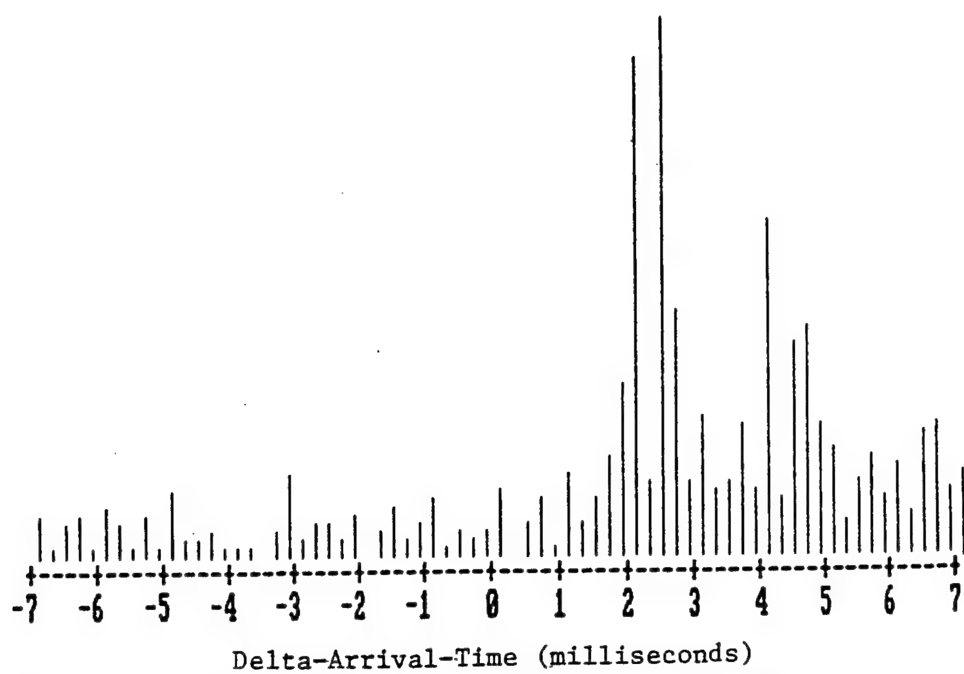


Figure 41. High S/N location of loose-screw leak

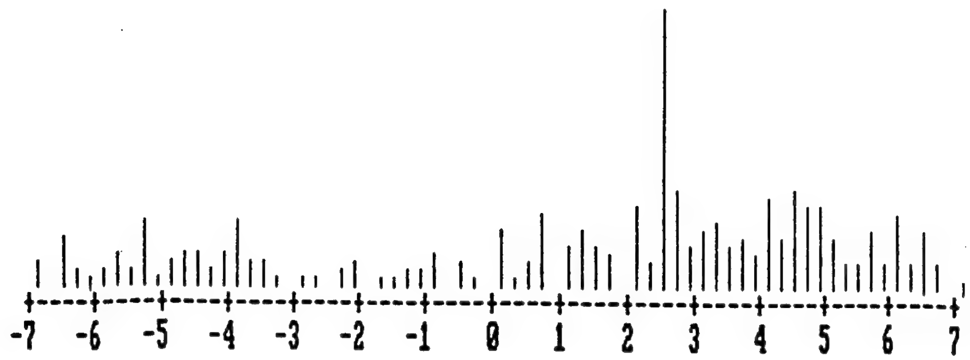


Figure 42. Location of loose-screw leak using events greater than 0.5 volts

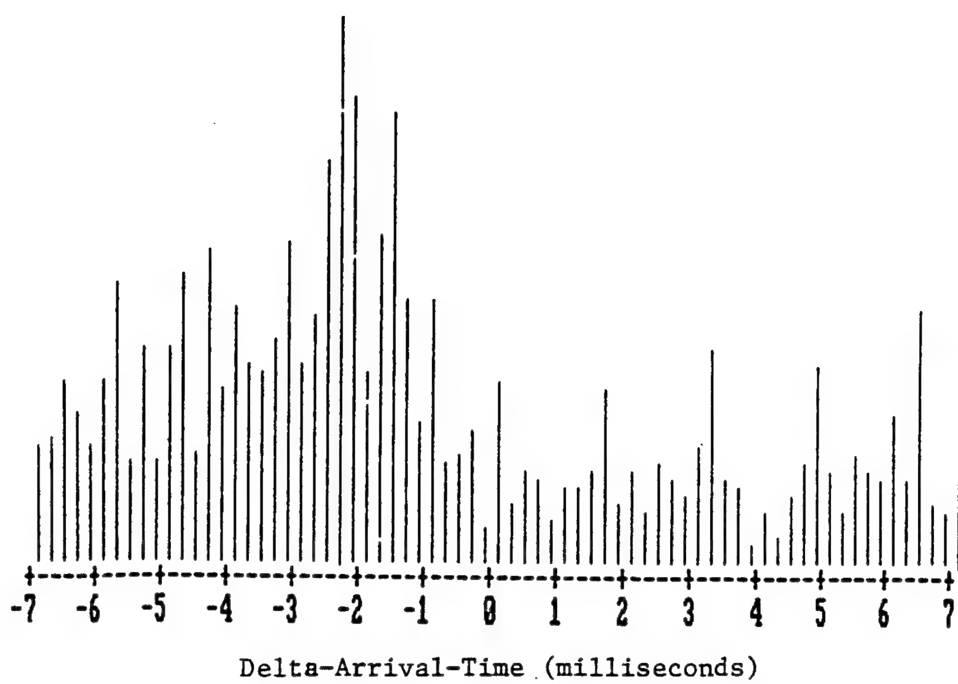


Figure 43. Location of loose-screw leak using events greater than 0.5 volts

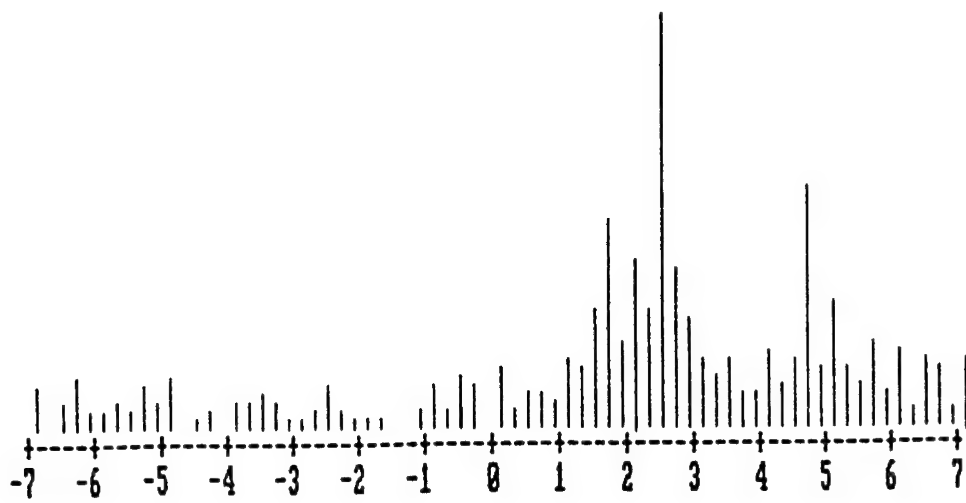


Figure 44. Location of 0.021-inch-diameter leak using events greater than 1 volt

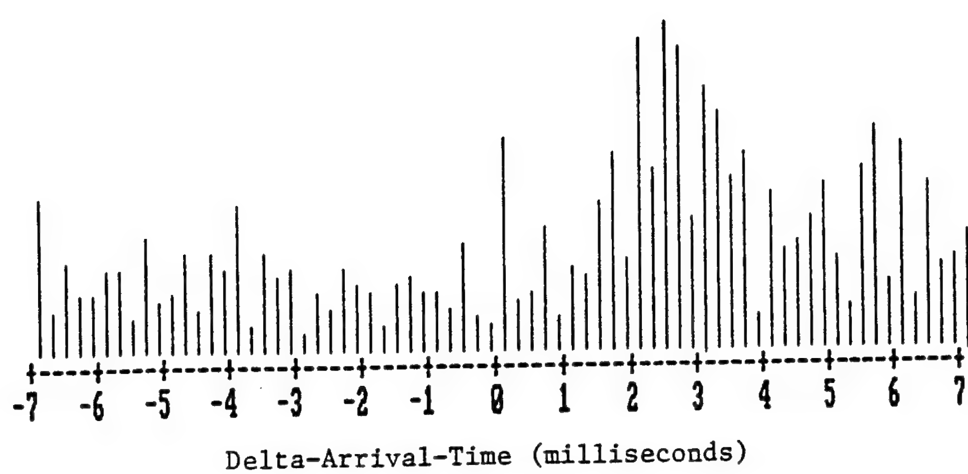


Figure 45. Location of 0.021-inch-diameter leak using events greater than 0.25 volts

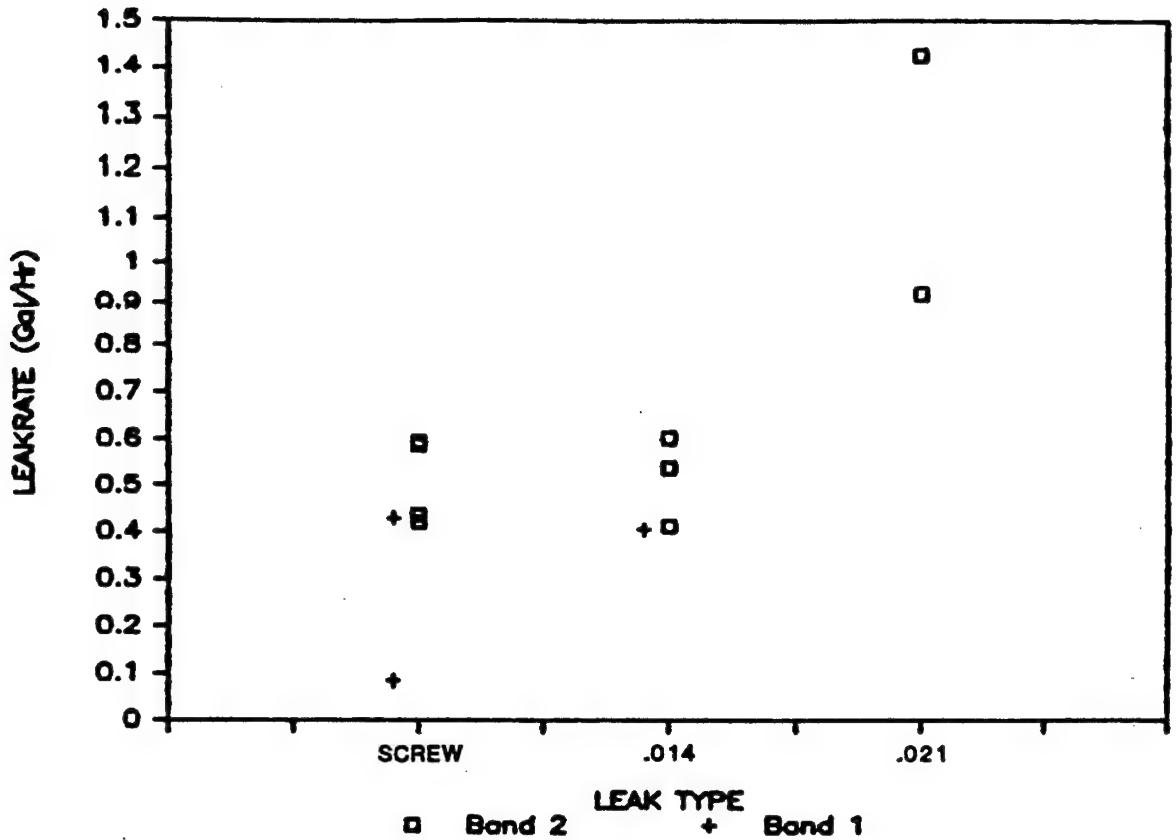


Figure 46. Summary of location-detection leak-test efforts

The pressure head was varied by changing the elevation of the water supply container. Almost all of the "location" tests were run with a 12-foot pressure head -- the maximum available in the test laboratory. The "statistical" tests were done over a zero to 15-foot range; further elevation was obtained by moving the supply container to an outside location.

The leak rates for the 0.014- and 0.021-inch-diameter holes remained fairly constant throughout the testing, (for a given pressure head) as shown by volumetric leak measurements done during each test series. Measurements of leak rate as a function of water-supply-elevation showed a slightly slower rate of increase with pressure than was calculated using a straight square-root-of-pressure dependence. The leak rate of the loose-screw leak was measured for each test; all of these tests involved a 12-foot pressure head.

Acoustic emission data were recorded for the 16 frequency bands ranging from 18 to 288 kHz. This data set was analyzed to determine the frequencies with the best signal-to-noise ratios for a particular mode of monitoring. The example data presented are for those frequencies selected as being the best.

Figure 5 shows comparative leak signals for JP-4, water, and gasoline for a 15-foot pressure head. It is seen that JP-4 produces about the same signal levels as water. Thus, for safety and convenience, water was used for this test program.

C. ACTIVITY-DETECTION DATA EXAMPLES

The data presented are limited primarily to AE frequency bands 1 and 2 (18 and 36 kHz) and accelerometer frequency band 10 (25 kHZ).

Figures 6 to 11 show leak signal levels versus pressure head for sandy, silty and clayey soils. Figures 6 and 7 are for respectively, 0.014- and 0.021-inch-diameter holes leaking into sandy soil. The larger hole emits higher average voltage signal levels with the highest level being for band 2, while the 0.014-inch-diameter hole has the highest level on band 1. The 0.014-inch-diameter hole shows background levels, i.e. no signal increase for zero to six feet of head. The leak signal level for the 0.021-inch-diameter hole increases above background starting at about three feet of head. All signals show more than 100% increase in their average-voltage signal levels.

Figures 8 and 9, for silty soils, show background level signals below about 12 feet of head. The band 1 signal for the 0.014-inch-diameter hole (Figure 8) increases very little; all other signals for both hole sizes show easily detectable increases.

Figures 10 and 11, for clayey soils, show significant signal increases at about eight-to nine-feet of pressure head, for both hole sizes and all three monitor bands. The slightly higher levels at zero elevation are due to laboratory noise. The accelerometer is particularly sensitive to floor vibrations which can be transmitted into the test fixture.

Figure 12 shows AE spectra for the 0.014-inch-diameter hole of Figure 6. The background spectrum represents zero-pressure data and the leak-signal spectrum is for 15 feet of pressure head. This indicates that bands 7-8 have higher signal levels than band 2, but about the same signal-to-noise ratio as band 2. There are detectable leak-signal levels even at the highest bands. This spectrum has more high-frequency signal than most of the leaks tested.

Figures 13 through 21 show signal-to-noise (S/N) ratios for the same test series used for Figures 6 through 11. All S/N values are calculated as the 15-foot leak-signal value divided by the zero-elevation, background-noise value.

Figures 13 through 15 show signal averages, signal standard deviations, and signal peak values (single highest value in a sample period), as a function of hole diameter. The data clusters for each of the 0.014- and 0.021-inch-diameter hole sizes are deliberately shifted slightly in the x-axis in order to allow a distinction of soil types. For example, the 0.0135-inch-diameter S/N values represent sandy soil data, the 0.014-inch-diameter values represent silt, and the 0.0145 values represent clayey soil data. The same left-to-right correspondence applies to the 0.021-inch-diameter data points.

The data of Figures 13 through 15 show that all S/N ratios are greater than 1.0, i.e. the leak signals are all greater than background noise. The values for the larger 0.021-inch-diameter hole are generally greater than for the 0.014-inch-diameter hole.

Figures 16 through 18 show the average, standard deviation and peak values versus monitor band. These reveal that no single band gives the highest S/N ratios for the three statistical distribution parameter.

Figures 19 through 21 show the average, standard deviation, and peak values grouped by soil type. All three types of data give good S/N ratios for the three soil types.

Figures 22 through 25 show data from the test series discussed above combined with data from other similar tests. These data were obtained using 12- to 15-foot pressure heads, and for average S/N values.

Figure 22 shows the pattern of higher S/N ratios for larger leak sizes. The screw leak has the lowest value. All of the 0.014- and 0.021-inch diameter hole tests yielded S/N ratios greater than 1.0, i.e. they were detectable as an increase above background noise.

Figure 23 shows good S/N values for all soil types. The offset data for each soil type represent, from left-to-right, hole sizes of 0.014 inches, 0.021 inches, and the screw hole.

Figure 24 gives the average S/N ratios as a function of the water leak rate. The lowest leak rate detected was about 0.19 gallons per hour, while the highest detected/tested was about 1.27 gallons per hour. All leaks of 0.014-inch-diameter size (about 0.4 gal/hr) and larger, were detected. Screw leaks smaller than this usually were not detected. The 0.2-gal/hr leak shown was detected while many others tested at this, and lower, flow rates were not detected.

Figure 25 shows only the band 2 data points of the Figure 19 data set. It clearly shows a relationship between average S/N values and leak rate.

D. LOCATION-DETECTION DATA EXAMPLES

Figures 27 through 46 show examples of leak detection by means of leak location using two AE sensors.

Figure 26 shows the location of an acoustic pulser attached to the pipe at a point about midway between the sensors. The location accuracy is better than 0.5 millisecond, this was verified by independent measurement using an oscilloscope. The close location resolution is shown by the approximately 75 location samples that accumulated within a single 0.2-ms division of the time scale.

Figures 27 through 30 show data for four separate leak tests performed for 0.014-inch-diameter holes leaking into sandy soil.

Figures 27 through 29 and Figure 2 show the distribution of event peak-values for a 0.014-inch-diameter hole leaking into sandy soil. Locations are shown in Figure 2 for all peaks measured for all data samples. Figure 27 data, with a 0.3-volt threshold, are very similar. Thus, few location events emitted by the leak had peak values lower than 0.3-volt. Figures 27 through 30 show the decreasing numbers of events versus increasing threshold value. Figure 29, with a 2.5-volt threshold, still shows a clear location.

Figures 31 and 32 show the random locations mapped when a leak, or other persistent acoustic source, is not present. The background-noise events which generate these random locations generally have low peaks, as shown by the large decrease in number of locations when going from zero- to a 0.3-volt threshold.

Figures 33 through 35 show three sets of zero-threshold leak data. Figure 33 has sharp location definition, using band 2 frequency, while the band 1 monitoring of Figure 34 gives positive but less definite resolution. Figure 35 shows location but also contains considerable noise. The noise is reduced and the signal is enhanced if one applies a 0.5-volt-threshold filter (Figure 36).

Figures 37 through 43 show data generated during loose-screw testing, when detection of holes significantly smaller than 0.014-inch-diameter was attempted.

Figures 37 through 38 show a relatively weak band 1 location; this could probably be improved by sustained monitoring.

Figure 39 shows a strong S/N location. The two sensor leads were reversed at their inputs to the monitoring system, causing the location to shift from -2.4 milliseconds to +2.2 milliseconds.

Figure 40 shows data for the smallest leak rate value successfully located. This was located on band 1, but could not be located on band 2. Many other attempts to locate leaks of this small diameter were unsuccessful. This leak rate is near the 0.1 gallon per hour goal.

Figures 41 through 43 are further examples of screw-leak location. All screw leaks which had a leak rate equivalent to the 0.014-inch-diameter hole leak-rate were successfully located. The sensor leads were alternately reversed going from the Figure 41 test to the Figure 42 test to the Figure 43 test.

Figures 44 and 45 show successful location of the larger 0.021-inch-diameter hole. Based on these experiments one would expect that any larger leaks would be successfully located; therefore, few location data were collected for larger leaks.

Figure 46 is a summary of the location-detection leak tests, where each point represents a test. All leaks of about 0.4 gallons per hour (or more) were successfully located. Those less than this were not, as a rule, successfully located. Both band 1 and band 2 produced good location data.

Leak rates were measured by a two-minute collection and weighing of the water leaking from the hole, at the 15-foot head level. Leak rates at lower elevations were determined from leak calibration curves, which were periodically verified.

E. DATA EVALUATION

The following conclusions are based not only on the data presented herein, but also incorporate years of relevant experience in this field.

Activity-Detection:

1. Leak rates of 0.4 gallons per hour and greater were reliably detected in the laboratory leak-test fixture, for pressure heads of 12-to 15-feet. An underground tank test should use this level of pressure, or greater.

2. Stimulation of the leak by changing the head pressure from a zero-to five-foot range to a 12-to 15-foot range would considerably increase the detection reliability over a procedure in which the tank is monitored at the 12-to 15-foot level only. For example, the drastic signal decrease which would occur when the head level was lowered from 15-to 5 feet would verify that the 15-foot source activity was being caused by a leak.

3. Tests involving sandy, silty and clayey soil types showed comparable test results. During this limited testing program, no single soil type was observed to have a more positive or more negative effect on the acoustic signals than any other soil type.

4. Calculation and comparison of statistical averages, standard deviations and peak values for the tests showed that these three distribution statistics are capable of indicating the presence of a leak. It appears that some acoustic characteristics are quite strong, and would be able to propagate a considerable distance in a containment structure such as an underground storage tank.

5. Both the AE sensors and the accelerometer proved capable of detecting leak signals, and should be used in future development in UST leak testing. Bands 1 and 2 for the AE sensor (18-and 36 kHz), and band 10 (25 kHz) for the accelerometer were observed to be particularly sensitive. However, significant signals were seen on other bands, and the most sensitive band often differed from one test to another. Future testing should involve most of the frequency range covered in this effort, i.e. 2.5-to 100 kHz.

Location-Detection:

1. Leak rates of 0.4 gallons per hour and greater were reliably detected and located in the laboratory test pipe, for pressure heads of 11-to 12 feet. An underground-tank-test procedure should use this level of pressure, or greater for detection/location.

2. Location-detection is not possible at low pressure heads, so stimulation by changing the inventory level from 15-to 5 feet is recommended in order to verify that the noise source is in fact, a leak.

3. The location tests involved only sandy soil. However, these data suggest that there would be no problem with location in silty and clayey soils.

4. Sorting and comparison of location-event peak values show high signal-to-noise ratios. For example, the data in Figures 27 and 29 show that many of the location events have peak values greater than a factor of 10 (20 dB) above the background acoustic-noise level. This signal strength will travel a considerable distance in a large UST, e.g. probably from one end to the other of an 80-foot long tank. Large 130-foot diameter, above-ground gasoline storage tanks which Pelagos crews have tested for floor leaks typically have considerably less than 20 decibels of acoustic attenuation across the diameter of the tank.

5. The AE sensors were used for leak location. The accelerometer's response characteristics make it unsuitable for this use. Future location testing should involve acoustic-emission bands 1 and 2.

SECTION V

CONCEPTUAL UNDERGROUND-STORAGE-TANK TEST PROCEDURES

A. PERIODIC TESTS

The activity-detection and location-detection methods can be applied in short periods of time. However, one basic requirement is that there must be no inventory inflow or outflow to the tank during the monitoring periods.

One should expect the activity-detection procedure to require about one half hour of "still" time, while the location-detection method could require up to one hour.

B. CONTINUOUS MONITORING

Both methods would be applicable for continuous monitoring. There are currently numerous continuous AE leak-monitoring systems in the nuclear and other industries.

In this UST application, the monitoring system would probably be interfaced with other instrumentation which could signal when the tank was being used, i.e. inflow or outflow. The leak-detection tests can only be performed when the tank is in a stilled condition.

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Two advanced acoustic-emission UST leak detection methods have been developed in this program. The activity-detection method statistically measures a greater activity in tanks having leaks. The location-detection method determines the presence of a dominant acoustic source in a leaking tank, and also indicates the approximate location of the leak source.

Both methods have a verification feature. By decreasing the pressure head in the tank to a low enough level, all leak signals can be eliminated.

The testing performed in this effort, using available equipment not designed for this application, shows a minimum-detection level of about 0.4 gallons per hour. It is expected that this capability can be considerably improved, to less than 0.1 gallons per hour for both methods by further testing and development.

B. RECOMMENDATIONS

It is recommended that the capability/methods evaluated in this Phase I effort be further developed, and applied in field test situations which would take place in a Phase II program.

REFERENCES

E650-78 - Recommended practice or mounting AE contact sensors

E750-80 - Practice for measuring the operating characteristics of AE instrumentation

1. Buck, J.S., L.J Graham, May 21, 1973. Acoustic Emission Testing Experience at the EBOR Reactor, PB 224 698, NTIS

2. Parry, D.L. and Robinson, D.L., "Elk River Acoustic Leak Detection Tests," IN-1371. Idaho Falls, Idaho: Idaho Nuclear Corporation, May 1970.

3. Smith, J.R., Rao, G.V. and Gopal, R., "Acoustic Monitoring for Leak Detection in Pressurized Water Reactors," Acoustic Emission Monitoring of Pressurized Systems, ASTM STP 697, ed. by Hartman and McElroy. Philadelphia: American Society for Testing and Materials, 1979, pp. 177-204.

4. Dau, G.J., "A review of Online Leak Detection Methods for Reactor System," 3rd Conference on Periodic Inspection of Pressurized Components. London: I. Mech. E., 1976, pp.67-73.

5. Pelagos Corporation, Applications Note 11, "Storage Tank Leak Detection", 1987.

6. Wickolaus C.M., "Acoustic Emission Monitoring of Above-Ground Storage Tanks", Materials Evaluation, March 1988.

7. Nondestructive Testing, Handbook, Volume 5, "Acoustic Emission Testing", 1988, American Society For Nondestructive Testing.

8. Air Force Contract F04611-81-0002 entitled "Automatic Leak Detection System", Air Force Rocket Propulsion Laboratory. Results presented in AFRPL-TR-81-93 and at JANNAF Propulsion meeting.